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of the
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on
Fire Safety

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PROCEEDINGS OF THE
INTERNATIONAL CONFERENCE ON FIRE SAFETY
VOLUME FIVE
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PAPERS PRESENTED AT THE
FIFTH INTERNATIONAL CONFERENCE ON FIRE SAFETY
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The Fifth International Conference on Fire Safety, the fifth of a series of annual conferences on the subject of fire safety, was held at the Plaza Airport Inn at the San Francisco International Airport in Millbrae, California on January 14 to 18, 1980.

This Proceedings volume contains the manuscripts or abstracts of twenty-nine of the thirty-one papers presented at the Conference. It is hoped that their publication will help the reader in the task of helping to make this world safer for its people.

Support for the Conference was provided entirely by the Conference participants. Their support is gratefully acknowledged.

Correspondence regarding the Conference and the Proceedings should be directed to Dr. Carlos J. Hilado, Product Safety Corporation, 1457 Firebird Way, Sunnyvale, California 94087.

The Sixth International Conference on Fire Safety will be held on January 12 to 16, 1981, at the Plaza Airport Inn at the San Francisco International Airport and at SRI International in Menlo Park.

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SMOLDERING ROUND ROBIN TESTS ON FLEXIBLE POLYURETHANE FOAM

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INTRODUCTION

Flexible polyurethane foams have replaced latex foam rubbers as cellular cushioning materials in recent years and have become one of the primary filling or stuffing materials used by the furniture and bedding industries. Marketing surveys indicate that the furniture industry has become the largest single consumer of flexible polyurethane foam, using approximately 45 percent of total flexible urethane production, according to recent estimates. Flexible urethane foam offers the furniture and bedding industries such outstanding properties as light weight, high relative strength, ease of fabrication, superior durability, and high resiliency. In addition, it can be formulated to meet many flammability requirements by the use of inherently fire resistant chemicals or the addition of specific high molecular weight flame retarding agents usually containing phosphorus and/or halogens.

It has long been recognized that "conventional" (i.e. non-flame-retardant) polyurethane foam may present a significant flammability hazard. These foams typically readily ignite from even small flaming ignition sources and, once ignited, often continue burning vigorously.

One might feel justified in asking why, in view of the potential flammability hazard, polyurethane foam has succeeded in dominating so many industrial markets. The answer is to be found in the fact that polyurethane foams possess so many other outstanding physical properties, unmatched by any other single product, that in many areas the potential flammability hazard has been, until recently, a risk worth living with.

REGULATION

During the past few years, consumers, consumer protection agencies, building code officials, state and federal governments have become intensely fire conscious. No longer are outstanding physical properties overriding potentially hazardous flammability characteristics. There is now concern that living and working environments be made as fire-safe as technology would allow.

As a result of a rash of state and federal flammability regulations and increasingly severe local building codes, there has been a dramatic swing in the types of flexible polyurethanes used in recent years. The proportions of

this swing can be seen from the latest statistics which indicate that less than 4 per cent of the total flexible urethanes produced in 1970 were flame retardant to any extent. This compares with in excess of 50 per cent flame retardant foam in 1974, and estimates that in 1979 it is anticipated that almost two-thirds of total urethane volume will consist of flame retardant grades.

The transition to flame retardant foams within the furniture industry has not been as impressive as in other industries, such as transportation, aviation, and carpeting, but marketing surveys show that the use of flame retardant flexible urethane foams by furniture manufacturers has risen from 1 percent in 1970 to an estimated 33 percent by 1978.

The potential fire hazard of flexible polyurethane foams can be as a result of a number of combustion situations: (1) ignition by a small ignition source, such as a lighted match or cigarette; (2) by acting as a combustible fuel source for an already burning large-scale fire; or (3) by insulating a fire to the extent that heat buildup is increased and damage possibly intensified.

Methods of reducing the flammability of flexible polyurethane foams have encountered numerous problems including permanence, odor, poor aging, charring, toxicity, and increased smoke production. However, recent developments in flame retardant systems claim to have overcome most of these problems.

Although there is presently no national flammability standard for upholstered furniture, a finding of need for such a standard has been published, and the National Bureau of Standards (NBS) has presented a draft proposed standard to the Consumer Product Safety Commission (CPSC).

Legislation was signed on August 10, 1972 requiring all upholstered furniture sold in California after April 1, 1975 to be made from fire retardant materials. The effective date of this legislation was amended, and the furniture regulations became effective on October 1, 1975.

Proposed performance standards were issued by the California Bureau of Home Furnishings in May 1974. These were amended on October 1, 1974 with the deletion of the requirements of Technical Bulletin 116 as a first generation standard. Final performance standards were issued in February 1975 and amended in March 1977. These standards require all filling materials used in upholstered furniture offered for sale in California to pass open flame and cigarette tests.

SMOLDERING

The primary hazards associated with fires where furnishings are the items first ignited are smoldering materials, specifically cigarettes, cigars, and pipes. Data contained in the computerized file of fire experience, Fire Incident Data Organization (FIDO), maintained by NFPA show that during the period 1971-1976 smoking materials were the source of ignition accounting for 79 percent of the injuries, 88 percent of the deaths, and 86 percent of the fire incidents in residential upholstered furniture fires. Cigarettes were the specific ignition source responsible for 60 percent of the injuries, 68 percent of the deaths, and 64 percent of all incidents in which upholstered furniture was the first item to ignite.

The typical scenario for fire fatality incidents where upholstered furniture is the first item to ignite would include an elderly smoker, whose reflexes have been dulled and mobility restricted by fatigue, old age, infirmity or the influence of alcohol and/or prescribed drugs, who falls asleep while smoking in the living room. The cigarette - probably a filter-tip - drops onto an item of furniture. The resulting smoldering combustion generates considerable quantities of smoke, toxic gas, and heat, with the most likely cause of death being anoxia resulting from inhalation of toxic combustion products.

The fire hazard of home furnishing materials may also involve flaming combustion, resulting from the contact of the material with flaming ignition sources, such as matches, lighters, candles, gas stoves, etc. However, technology is generally available to chemically modify the properties of many materials such that they are to some extent fire or flame resistant.

The fire hazard of materials associated with mattresses and upholstered furniture usually involves smoldering combustion, resulting from contact with smoldering ignition sources, such as cigarettes, cigars, and pipes. The effort which has gone into modifying the smoldering properties of materials has been much less than that expended in the area of flaming combustion. Treatments which are intended to reduce flammability are usually ineffective as smoldering inhibitors, and sometimes only compound and intensify smoldering problems. Commercially, very few smoldering inhibitors are available to the manufacturer of materials intended for home furnishings use.

The mechanism of combustion and pyrolysis of materials is a complicated phenomenon and involves a complex series of reactions that can occur concurrently and not necessarily simultaneously. Two distinct types of combustion can occur: (1) smoldering; and (2) flaming.

Smoldering, simply oxidation of carbonaceous char by air, forming carbon monoxide and some carbon dioxide, is characterized as burning and smoking or wasting away by a slow suppressed combustion without flame.

In contrast, flaming combustion is a rapid oxidation of volatile pyrolysis products and occurs in the gaseous phase. The burning gases provide sufficient thermal energy to further degrade the material. This process can continue until only the solid carbonaceous residue remains. Smoldering combustion is not necessarily a sequel to flaming combustion, nor is flaming combustion a necessary or sufficient condition for initiating smoldering combustion.

Over the years considerable effort has been expended in understanding the mechanism of flaming combustion. Significant success has been attained in modifying the flaming properties of materials. Flame inhibiting chemicals and fire resistive materials are now a recognized part of our living environment, and vapor phase and condensed phase fire retardant chemicals are readily available. In the area of flaming combustion inhibition, it may be truthfully said that the chemicals industry has identified the problem and has successfully accepted the challenge.

Flaming combustion is a highly visible, readily identifiable phenomenon with the potential for great property damage and loss of life. It has rightly attracted great attention. However, smoldering combustion is a less visible, almost hidden

insidious killer claiming the lives of perhaps thousands of Americans each year. Yet little obvious intensive effort has been evident in attempting to inhibit or modify smoldering in typical home furnishings materials. It would appear that one of the technological challenges facing industry today involves an in depth look at furnishing smoldering problems along with investigations into smoldering behavior modification. The commendable effort of recent years in the area of flame retardancy should now be supplemented by an equally intensive effort into smolder resistance of materials. Fires in homes originate in two basic ways: (1) flaming; and (2) smoldering. We have chosen to focus on one and until recently ignore the other. The time has come to remedy that omission.

CALIFORNIA BUREAU OF HOME FURNISHINGS TECHNICAL BULLETIN 117

California Technical Bulletin 117 requires that all components used as furniture fillers resist smoldering when subjected to a single cigarette covered by one layer of cotton bed sheeting material the intent of this performance test being to screen out materials of extreme smoldering qualities. However, this procedure in no way indicates the relative or comparative smoldering characteristics of similar materials.

In general, although there are notable exceptions, polyurethane foams exhibit good resistance to sustained smoldering from small smoldering ignition sources, such as single cigarettes. The use of a single lighted cigarette does not serve as a good smoldering screening test for normal flexible polyurethanes nor does it actually duplicate a realistic test condition representative of real life hazard.

In recent years, researchers have published a variety of technical papers which relate to the smoldering properties of flexible urethanes. These papers have variously suggested that the mechanism of smoldering in flexible polyurethane might be affected by such factors as foam density, porosity, nature of the polyol, overall chemical structure, physical properties, and the tendency of the foam to form carbonaceous char or liquid tar. In spite of the seeming uncertainty as to the true mechanism of smoldering in flexible polyurethane foams, one conclusive fact has emerged from all of these studies: Individual foams in a normal population of foams will exhibit grossly differing smoldering properties when evaluated by an appropriate test procedure. In other foams, some foams appear to inherently inhibit smoldering much more readily than others, and conversely, some foams are much more susceptible to smoldering than are other formulations.

In actual use, flexible foams are rarely used in isolation or in their manufactured form. Most often, these foams are used in combination with a variety of other component materials. It is well recognized that the flammability properties of component materials may bear no relationship to the actual flammability performance of finished products consisting of a number of component materials. The synergistic or antagonistic effects of combinations of components or materials are well documented.

In furniture and bedding applications, urethanes are always used in combination with other component materials, such as fabrics and perhaps other stuffing or filling materials. The primary fire hazard of such systems involves the accidental dropping of a lighted cigarette on an article of furniture or bedding

and a resulting smoldering combustion of the system. A highly typical system for such a scenario would include the following components:

- (a) A lighted cigarette accidentally dropped on a furniture piece. The cigarette may also be inadvertently covered by an article of clothing, newspaper, etc.
- (b) An upholstery fabric, consisting of cellulosic fibers such as cotton and/or rayon, with a fairly heavy weight (greater than 15 oz./sq.yd.), and having no back coating.
- (c) A furniture piece with both horizontal and vertical (or almost vertical) surfaces which form a crevice for the lodging of the cigarette.
- (d) A substrate material immediately beneath the fabric, consisting of cotton batting or polyurethane foam.

Research has shown that furniture systems consisting of all of the above components would sustain smoldering combustion more than 90 per cent of the time.

POLYURETHANE FOAM STUDIES

In January 1977, the Bureau tested every polyurethane formulation manufactured in California which was being marketed as complying with Technical Bulletin 117. In all a total of more than 100 foams, representing the product of seven manufacturers, were evaluated. Along with vertical flame tests, an intensive smoldering study of each foam was conducted. Each urethane in this survey was subjected to eight (8) different smoldering protocols in an effort to accurately characterize their smoldering qualities. Briefly, the eight smoldering procedures were as follows:

1. One cigarette - covered
2. Two cigarettes - covered
3. Three cigarettes - covered
4. Smoldering fabric - uncovered
5. Cigarette/fabric - uncovered
6. Cigarette/fabric - covered
7. Radiant heat
8. Furniture mock-up system

Among the conclusions of this study were the following:

1. Good performance in vertical flame tests does not guarantee inhibition to smoldering combustion.
2. The mechanism of smoldering combustion of urethane formulations is not as clearly understood as is flaming combustion mechanism, and the reasons that one foam formulation smolders readily and another similar formulation not at all, have not been clearly delineated.
3. A wide variety of smoldering results was obtained in this study, often with little relationship to results obtained in vertical flame testing.
4. Whether by design or fortuitously, 43 percent of the foams in the study performed well in both smoldering and flaming tests. This suggests that techniques are available, either known or unknown, to formulate flexible urethanes with both good flaming and smoldering resistant properties. A thorough evaluation of each individual formulation may be necessary to pinpoint those factors which promote good resistance to both flaming and smoldering modes of combustion.

A thorough evaluation of the above study indicates that, although severe, the miniature furniture mock-up (procedure 8) creates test conditions which are very representative of real-life conditions, and that conceptually this testing scheme might prove to be an admirable device for evaluating the relative smoldering properties of a wide variety of materials.

In many previous studies, the small-scale furniture mock-up has been used to offer great flexibility at very low cost. A large population of fabrics has been evaluated with an almost equally large population of substrates and combinations of substrates, and the interaction between the cover fabric and the adjacent substrate material has been carefully studied. In the course of this previous work, it became readily apparent that when one of the primary components of the mock-up system was standardized, that is, a standard fabric or a standard substrate, the smoldering properties of the system varied with the nature of the varying component. For example, with a given standard fabric in combination with a variety of substrate materials, it can be shown that the smoldering characteristics of the system can vary dramatically as the substrate is changed. Further, it can be shown that variations in smoldering performance are observed even within generic classes of substrates.

In early 1978, the Bureau conducted ⁽²⁷⁾ ~~a~~ ^{was conducted} study in which several hundred flexible polyurethane foam formulations were evaluated for smoldering potential in ~~the~~ ^a small-scale furniture mock-up system in combination with a standard uniform upholstery fabric (100% cotton) ~~18 oz./linear yd.~~. All foam test panels were of uniform size and the ignition source was a lighted ~~Pall Mall~~, non-filter king cigarette placed at the crevice created by the horizontal and vertical panels and covered by one layer of 100 percent cotton sheeting material. Measurements of percent weight loss, percent char, percent residue, and maximum char depth of foam panels were made; all tests were conducted in triplicate. Test results of this study showed gross differences in the smoldering properties of individual foams in ~~this~~ ^{the} population of foams.]

When evaluated by this technique, 30 percent of foams tested showed excellent resistance to smoldering and yielded 95 percent or greater of non-smoldered residue. The data also indicated that 50 percent of tested foams yielded about 85 percent or greater of non-smoldered residue. At the other end of the scale, the data showed about 15 percent of the foams tested showed a definite tendency to sustain smoldering under these test conditions, yielding 70 percent or less of non-smoldered residue.

The test data also showed that flaming combustion was observed as a sequel to the smoldering with about 4 percent of the urethanes tested. An analysis of the test data for reproducibility indicated fairly good reproducibility for this type of procedure.

PROPOSED TEST METHOD

[As a result of this study a] proposed "smoldering screening test for flexible polyurethane foams used in upholstered furniture" was developed by the Bureau. This suggested procedure was mailed out for comments and suggestions, and for recommendations as to appropriate test criteria on June 23, 1978. Following a ^{author} review of the written replies and after informal discussions with many other interested parties, a revised proposed test procedure was developed by the Bureau early in 1979. ^{model 27}

INTER-LABORATORY ROUND-ROBIN

At the request of the Bureau a committee met in January 1979 to assist the Bureau in setting up a procedure to conduct an inter-laboratory round-robin study of the

revised proposed "smoldering screening test for flexible polyurethane foams used in upholstered furniture". The following laboratories were invited and agreed to participate in this round-robin study:

| | |
|------------------------------------|---------------------------------------|
| Velsicol Chemical Corporation | Olin Research Center |
| United Foam Corporation | Monsanto Industrial Chemicals |
| Union Carbide Corporation | Mobay Chemical Company |
| Tenneco Chemicals | Dow Chemical |
| Stauffer Chemical Company | CPR Division, The Upjohn Company |
| Reliance Upholstery Supply Company | California Bureau of Home Furnishings |

Each participant was mailed a copy of the revised test procedure, instructions and report sheets, along with samples of all test materials. The test foams chosen for the study were:

| Foam | Type | Density | ILD |
|------|--|---------|-------|
| A | High Resiliency | 3.0 | 32-36 |
| B | Conventional Fire Retardant | 2.5 | 34-37 |
| C | Conventional Fire Retardant | 1.2 | 29 |
| D | Conventional Fire Retardant | 1.85 | 33 |
| E | Conventional Non-Fire Retardant | 1.2 | 29 |
| F | High Resiliency | 3.0 | 34 |
| G | Conventional Non-Fire Retardant | 1.45 | 25 |
| H | High Resiliency | 2.0 | 10 |
| I | Conventional-Filled Non-Fire Retardant | 2.9 | 39 |
| J | Conventional Fire Retardant | 1.45 | 32 |

All foam test specimens and fabric coverings were cut, coded, and randomized at the Bureau prior to shipping to participating laboratories. Participants were instructed to follow exactly the testing provisions of the revised test, with the exception that six (6) tests were to be conducted on each individual foam instead of three (3), with no more than three (3) tests on any individual day.

RESULTS

The data obtained from the 12 round-robin participating laboratories are too extensive to be included in this paper, and can be obtained from Laboratory Report No. SP-79-1, "Flexible Polyurethane Foam - A Smoldering Study", issued in November 1979 by the Bureau of Home Furnishings.

TEST CRITERIA

The intent of the round-robin study was to have a number of independent laboratories use a common test procedure to generate data from an identical population of test materials, the ultimate objective being to evaluate the reliability, reproducibility and precision of the suggested test procedure. For the purposes of this study, it was felt to be unnecessary and not desirable to evaluate the test materials by an type of pass/fail criteria which might influence the basic intent of the study.

However, for regulatory enforcement purposes, it becomes necessary to establish some type of standard and/or performance criteria by which one makes the decision that a certain material is satisfactory or unsatisfactory for use in a certain application.

To post-evaluate the test foams used in this round-robin study and particularly to evaluate inter-laboratory reproducibility to selected criterion, the data of this study was evaluated by the Bureau under the pass/fail criteria scheme shown in Figure 1.

To some extent pass/fail criteria of this type tend to be somewhat arbitrary and are often based upon impulse and conjecture rather than hard fact. In this instance, the limiting figure of 80 percent non-smoldered residue was selected because:

- (a) Based upon the data obtained, 80 percent non-smoldered residue appears to be rather easily attainable, with about a minimum of 60 percent of a typical population of California grade foams already performing at this level. In other words, technology is readily available to formulate urethanes that will readily meet the suggested test criteria.
- (b) After having worked with the test procedure for a number of years and having gained a good understanding of the relative severity of the procedure, it appears that an 80 percent level of non-smoldered residue is a minimum realistic initial performance level under these conditions for urethanes formulated for furnishings applications.

Table 1 indicates an evaluation of each foam in the study for each laboratory by the 80 percent pass/fail criteria shown in Figure 1. A review of this table indicates the following:

- (a) All 12 laboratories were in total agreement on 3 of the 10 foams.
- (b) At least 11 laboratories, although not necessarily the same 11 laboratories, were in agreement on 9 of the 10 test foams.
- (c) Only test foam E gave results based upon pass/fail criteria with significant disagreement between laboratories.
- (d) Of the 12 participating laboratories, 6 were in total agreement on all test foams, and 4 of the remaining laboratories agreed on 9 of 10 foams.
- (e) Of the total of 120 pass/fail determinations made, only 9 differed from the norm, indicating a greater than 90 percent agreement on all foams for all laboratories.
- (f) The results of laboratory 31 differed from the norm, more frequently than any other laboratory due to consistently higher than average values of non-smoldered residue.
- (g) Deletion of the test results for laboratory 31 and for foam E show a 97 percent agreement for all other laboratories on all other foams.
- (h) Looking at the raw data for the 9 pass/fail determinations which differed from the norm, it may be observed that 6 of the outliers are within ± 4 percent of the 80 percent test criteria.

CONCLUSION

It may be reasonably concluded that this procedure offered good reproducibility between laboratories when evaluated by criteria such as suggested above. Although the test precision in terms of absolute numbers is only fair, this is to be expected for this type of smoldering evaluation. It would appear from all the data generated in this study that the suggested smoldering test procedure does serve as a viable screening test for flexible polyurethane foam, with inter-laboratory reproducibility perfectly satisfactory under pass/fail criteria test conditions. The study illustrates the necessity for close attention to detail as far as the test procedure is concerned, if realistic, reproducible results are to be produced.

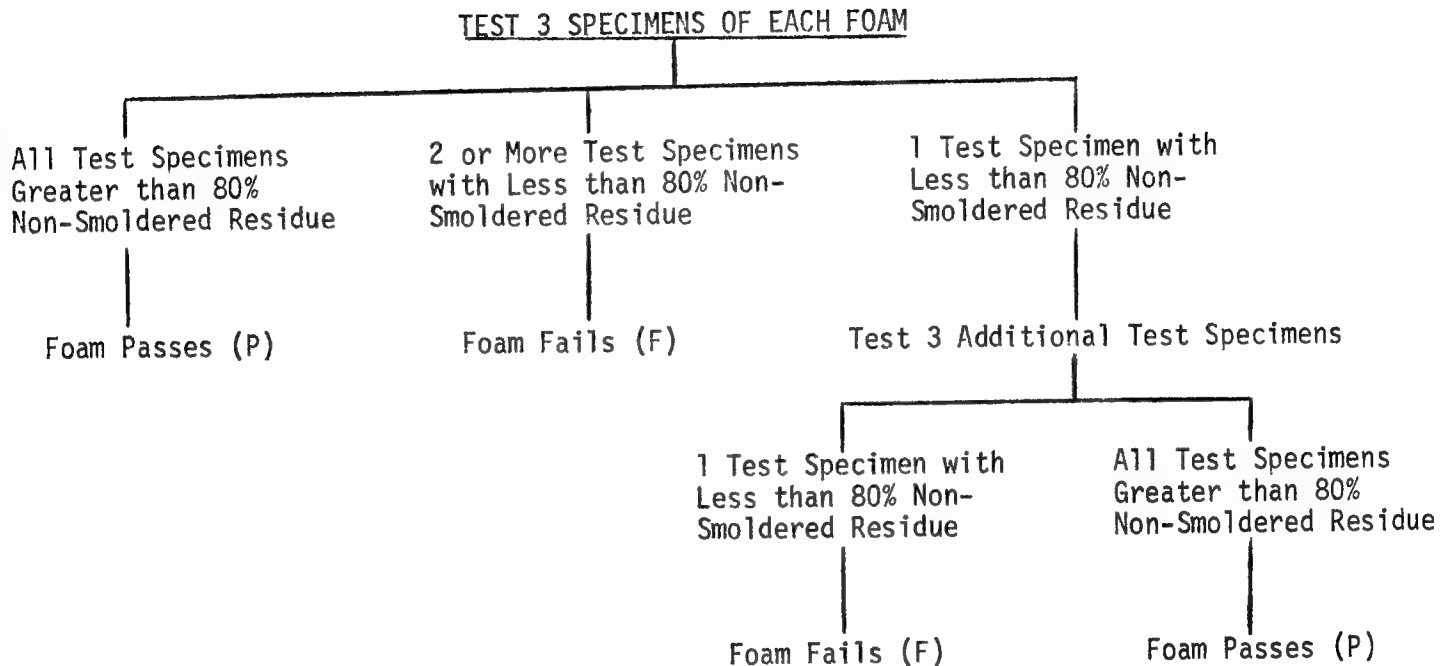


Figure 1. SMOLDERING PASS/FAIL TEST CRITERIA

Table 1. . ROUND-ROBIN FOAMS EVALUATED BY TEST CRITERIA

| Laboratory | Foams | | | | | | | | | |
|------------|-------|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J |
| 20 | P | P | F | F | F | P | F | P | F | F |
| 21 | P | F | F | F | F | P | F | P | F | F |
| 22 | P | P | F | F | P | F | F | P | F | F |
| 23 | P | P | F | F | P | P | F | P | F | F |
| 24 | P | P | F | F | F | P | F | P | F | F |
| 25 | P | P | F | F | P | P | F | P | P | F |
| 26 | P | P | F | F | P | P | F | P | F | F |
| 27 | P | P | F | F | P | P | F | P | F | F |
| 28 | P | P | F | F | P | P | F | P | F | F |
| 29 | P | P | F | F | P | P | F | P | F | F |
| 30 | P | P | F | F | P | P | F | P | F | F |
| 31 | P | P | P | P | P | P | F | P | F | P |

P = PASS

F = FAIL

A Combustibility Study of Cellulose Insulation

By

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Presented at the 5th International Conference on Fire Safety
January 14-18, 1980.

Cellulose insulation has certainly received a large amount of publicity with respect to its fire safety, and although many people will claim that there has been an over-reaction on the part of government regulating authorities and the press, those familiar with the combustion characteristics of cellulose recognise that wood, cotton, as well as ground up newspaper will burn unless treated with appropriate chemicals. With cellulose insulation, the concern is that the material, when installed in an attic, may result in a fire should it come into contact with an overheated electrical device, or a heat source such as recessed lighting fixture, trouble lamp, furnace flue or chimney, or even an open flame such as a match, lighter or plumber's torch. It is, therefore, essential to ensure that the chemicals applied to the material not only retard the flaming combustion, but also the smouldering combustion of the material.

Borax and boric acid have long been recognised as flame retardant chemicals for cellulosic textiles. Consequently, it is not too surprising to find their widespread use with cellulose insulation. Work at the U.S. Department of Agriculture's Southern Regional Research Centre has already shown that boric acid is the effective chemical of choice to retard the smouldering combustion of cotton batting used in mattresses.[1] In addition, it has also demonstrated the deleterious role of the sodium ions[2] associated with borax in retarding smouldering combustion. However, in the case of cellulose insulation, it is desirable to determine the optimum concentration of borax and boric acid to achieve both smoulder resistance and flame resistance.

In our laboratories we have investigated the role of borax and boric acid on the flame resistance and smoulder resistance of treated cellulose insulation[3], and our findings are summarised in Figure 1. In this figure we have drawn boundary lines to indicate those formulations, which when applied to cellulose insulation, give materials that will meet Canadian standards for

fire performance and smoulder performance. The vertically oriented line marks the demarcation between the acceptable and unacceptable materials with respect to flammability, whilst the horizontal line represents the demarcation with respect to smoulderability (in both cases the shaded regions represent formulation that give acceptable materials). This graph clearly demonstrates the importance of boric acid to achieve smoulder resistance. However, in order to achieve acceptable flame retardancy, it is necessary to incorporate some borax into the formulations. The double shaded area, therefore, represents the only formulations capable of providing both smoulder and flame resistant materials. In terms of economy, the formulation should be as close as possible to the intersection of the two demarcation lines. However, it should also be remembered that the closer the formulation approaches these two demarcation lines, the smaller is the margin of safety. It may therefore be concluded that a 1:7 borax:boric acid formulation at a treatment level of 16 parts per one hundred of cellulose insulation should provide the required protection to both smouldering and flaming combustion at the least cost whilst allowing some margin of safety.

In addition to looking at borax and boric acid, we have also examined several other chemicals[4] which have been proposed as smoulder retardants for cotton batting. The effectiveness of these chemicals as smoulder retardants for cellulose insulation is summarised in Table I. In this table the degree of smoulder retardancy is being compared. Here we compare the relative rate to achieve a 15% weight loss with a blank untreated material. Thus, compounds which give values close to 1 have smouldering rates comparable to untreated insulation. The smaller the value the greater the smoulder resistant characteristics until a material becomes resistant to smouldering combustion when it is designated as SR (smoulder resistant). It can be seen from this Table that in addition to boric acid, ammonium sulphate is the only one of these chemicals that is an effective smoulder retardant when employed on its own. However, in view of the high cost of boric acid, it is always possible that some of these other materials may be effective when used together with borax and boric acid. The results obtained, with a limited number of formulations are given in Table II. Obviously the ammonium phosphates and sulphates along with alum and aluminum sulphate are capable of acting as smoulder retardants when used in conjunction with borax and boric acid. However, in terms of other properties such as corrosiveness and fungal resistance, the ammonium salts are generally not acceptable. Aluminum sulphate, on the other hand, is used extensively by the industry and therefore its effectiveness, along with borax and boric acid, was investigated in detail.[5]

The work involved in determining the effectiveness of a three component system is very involved and time consuming and the data

presented in Figure 2 represent several months work. Each triangular plane represents a different treatment dosage (24 pph, 18 pph and 12 pph). Points on the triangular plane represent specific formulations containing borax, boric acid and aluminum sulphate. The apices of each triangular plane refers to formulations containing 100% of a material, whilst the labelled side opposite contains 0% of that material. Thus, on proceeding from a base to the opposite apex, the percentage concentration of that chemical in the formulation increases from 0 to 100%. Meanwhile, a point in the centre of a triangular plane would have a formulation containing 33 1/3% borax, 33 1/3% boric acid and 33 1/3% aluminum sulphate. The shaded regions on each plane correspond to formulations at that dosage level which give cellulose insulation of acceptable smoulder resistance. Formulations which give non-smoulder resistant materials fall outside of this shaded area. The importance of boric acid in achieving smoulder resistance is clearly evident from this graph. Whilst there is a large number of formulations capable of providing smoulder resistant materials at the 24 pph level, when the dosage is reduced to 18 pph and 12 pph the number of these formulations is reduced. At the same time the percentage of boric acid in the formulations required to maintain smoulder resistance increases.

The smoulder resistance, however, is only one half of the picture. It is necessary to superimpose on top of this figure the data for flame retardancy (Figure 3).

At the 24 pph level none of the formulations have problems in achieving the required flame retardancy, hence the double shaded region represents all formulations which give acceptable flame and smoulder resistance. At the 18 pph level, however, it will be noted that a majority of the smoulder resistant materials now fail the flame retardancy requirements. At the 12 pph level the number of formulations meeting both requirements is extremely small.

In addition to utilizing the cigarette test to evaluate the smoulder resistance of cellulose insulation we have developed a new test methodology for evaluating this property.[6,7] The basics of the test equipment are shown schematically in Figure 4. Essentially it consists of a 100W electrical cartridge heater 10 mm in diameter and 80 mm long which is embedded into the centre of the cellulose insulation contained in a 170x90 mm Pyrex crystallization dish. Alongside the heater is placed an iron/constantan thermocouple. The output from the thermocouple is split into two signals; one is fed directly to the strip chart recorder whilst the other is electronically processed to give the first order derivative.

With this equipment we have been able to monitor two aspects of the smouldering combustion process, which can best be understood by examining Figure 5 which represents schematically what happens in the experimental set up just described. Line A represents the heat being supplied by the heater, B is the heat being generated by the smouldering combustion of the cellulose insulation and C the

heat lost to the surroundings. In order for a material to undergo self-propagating smouldering combustion, it must receive a certain minimum amount of energy from the heater. With a fixed heater voltage this energy may be related to a certain minimum time that the power must be supplied and represents a threshold condition. This threshold condition for the initiation of smouldering combustion is obviously related to the total heat balance of the system as a whole. The heat being supplied to the system comes from two courses, (i) that produced by the heater and (ii) that produced by the exothermic oxidative degradation of the cellulose associated with the smouldering process. When the heat liberated by this exothermic degradation is sufficiently large (i.e. greater than the total heat loss of the system) the power to the heater may be switched off and the process of smouldering combustion will be self-propagating. The time to reach this condition is denoted as t_{sp} and is considered as the time to initiate self-propagating combustion. When this condition is achieved, the heat being generated by the system will be greater than the heat lost, and will cause a further increase in temperature with a corresponding increase in the rate of degradation and heat feedback to the system.

Before this self-propagating condition is reached, however, the system goes through a transient state of smouldering combustion. The onset of this transient smouldering combustion in our equipment is detected by an inflection in the temperature profile, and is felt to correspond to the point at which sufficient heat has been supplied by the heater to establish the smouldering process. However, if the external heater supply was switched off at this point, the smouldering would self-extinguish because the heat being generated by the combustion is still less than the heat being lost by the system as a whole.

In our experimental method for a specific power level supplied to the heater, we measure two values

- (i) the time to initiate transient smouldering combustion t_{tr} and
- (ii) the time to initiate self-propagating smouldering combustion t_{sp} .

The variation of these two values as a function of applied power level to the heater is depicted in Figure 6. These results were obtained with cellulose insulation treated at a 24 percent add-on level of a 2:1 borax:boric acid formulation. The shape of these curves is not surprising. At the lower power levels relatively long times are required to initiate the smouldering, both transient and self-propagating, whilst at the higher power levels the initiation times are relatively short but the discriminating ability of the method is reduced. For most practical purposes, it is satisfactory to use just one power level. The data presented in the remainder of this paper will consider the results obtained with just one power level (i.e. 17.5 watts).

When this method was applied to cellulose insulation treated with a 2:1 borax:boric acid formulation at various dosage levels the results presented in Figure 7 were obtained. The solid line represents the time to initiate self-propagating combustion, whilst the broken line represents the time to initiate the transient combustion. Both initiation times show a dependence on the percentage chemical add-on i.e., as the weight of added chemical on the cellulose increases so does the time to initiate both the tentative and self-propagating combustion.

When the method was used to evaluate the effect of borax:boric acid ratio in a treatment formulation at a dosage level of 20% the results shown in Figure 8 were obtained. This graph indicates that the composition of the treatment formulation has little or negligible effect upon the time to initiate the transient smouldering combustion, whilst having a pronounced effect upon the time to initiate the self-propagating combustion.

In view of the recognised important role boric acid plays in the chemistry of the smouldering combustion of cellulose, the difference between t_{sp} and t_{tr} can be regarded as a measure of the chemical retardation. The apparent insensitivity of t_{tr} to variations in borax:boric acid composition, whilst being sensitive to percent chemical add-on, however, would suggest that this parameter is probably a measure of the physical retardation associated with chemical loading. In this physical process the chemicals act as an inert filler which reduce the concentration of the fuel. Alternatively, it is also possible that the chemicals have an influence on the thermal conductivity of the insulation affecting the rate of heat loss.

Thus, by comparing the t_{sp} and t_{tr} data, it is possible to obtain a clearer understanding of the smouldering combustion process. The method is also capable of discriminating between chemicals which act by physical interactions as opposed to species which play a chemical role. Applying this methodology to a variety of chemical systems should provide the manufacturer of cellulose insulation with much needed technologic information to help solve many of the problems associated with producing a fire safe product.

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TABLE I

Effect of Various Chemicals at the 24 pph Treatment
Level on the Relative Rate of Smouldering Combustion

| <u>Chemical</u> | <u>Relative Rate of Smouldering</u> | <u>Test Density kg/m³</u> |
|-----------------------------------|---|--|
| Untreated | 1.00 | 36 |
| Boric Acid | SR | 44 |
| Borax | 1.00 | 48 |
| Diammonium hydrogen phosphate | 0.88 | 40 |
| Monammonium dihydrogen phosphate | 0.92 | 39 |
| Sodium phosphate tribasic | 1.73 | 41 |
| Ammonium sulphate | SR | 38 |
| Alum, aluminum potassium sulphate | 0.83 | 43 |
| Aluminum sulphate | 0.72 | 48 |
| Aluminum trihydrate | 0.71 | 34 |

TABLE II

Relative Rates of Smouldering Combustion of Cellulose
Insulation Treated with Three Component
Formulations at the 24 pph Treatment Level

| <u>Chemical X</u> | Formula <u>2:1:2</u> | B:BA:X <u>6:3:1</u> |
|-----------------------------------|-------------------------|------------------------|
| Boric Acid | 0.66 | 0.77 |
| Borax | | 0.87 |
| Diammonium hydrogen phosphate | SR | SR |
| Monammonium dihydrogen phosphate | SR | 0.60 |
| Sodium phosphate, tribasic | 0.97 | 0.83 |
| Ammonium sulphate | SR | 0.58 |
| Alum, aluminum potassium sulphate | SR | 0.68 |
| Aluminum sulphate | SR | SR |
| Aluminum trihydrate | 0.81 | 0.78 |

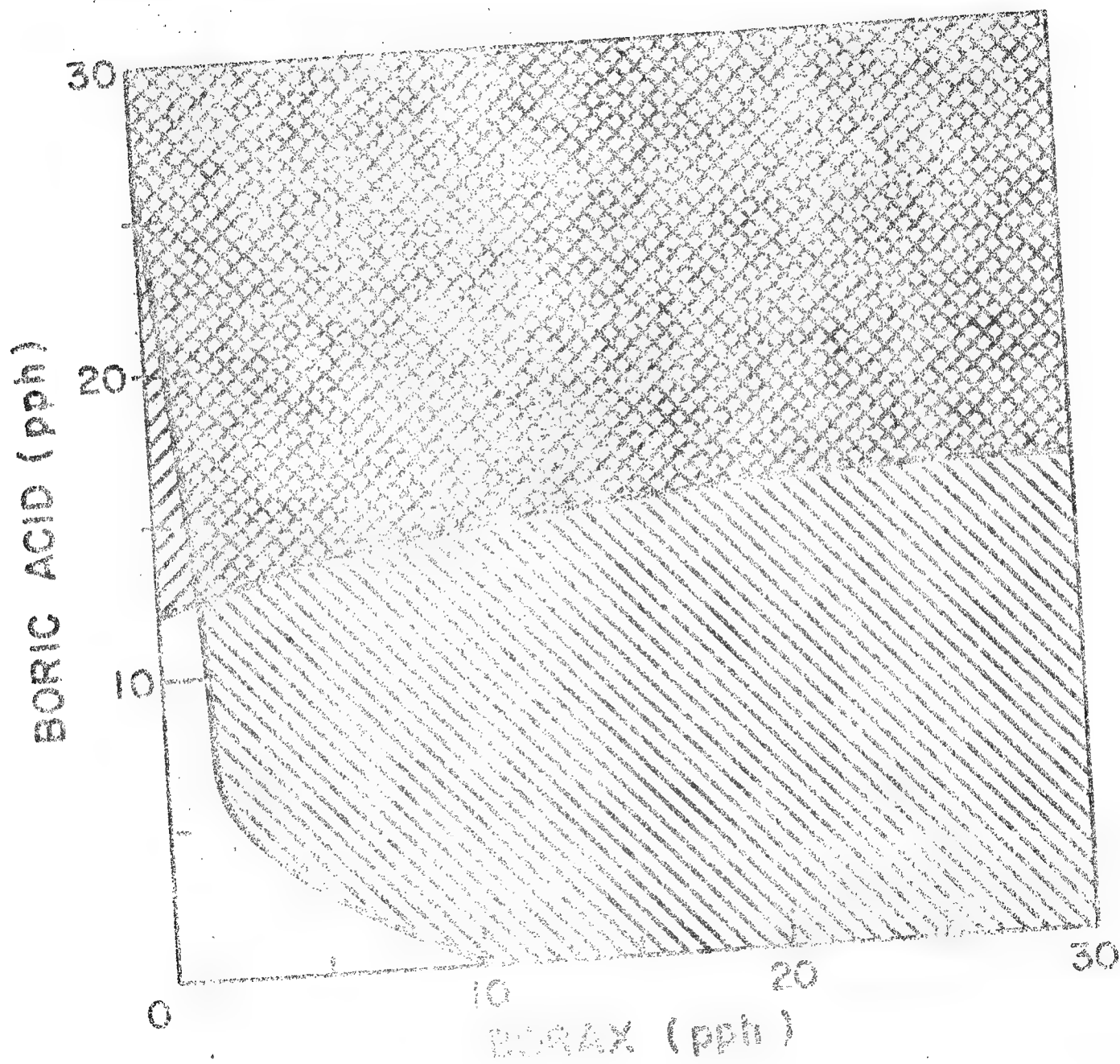


Figure 1. Amounts of borax and boric acid required in the treatment simulations to achieve specified

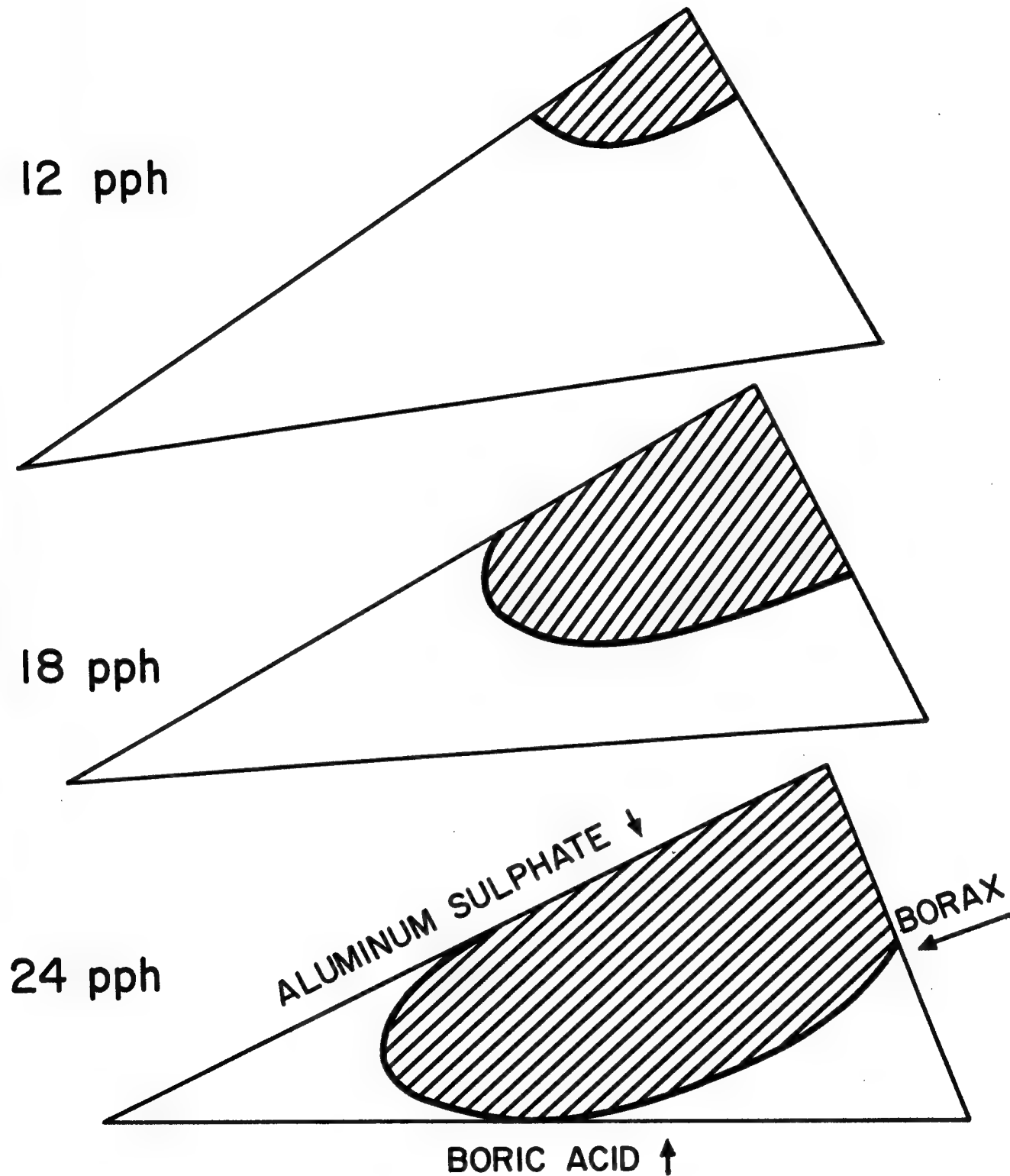


Figure 2. Formulations of borax, boric acid and aluminum sulphate capable of retarding the smouldering combustion of cellulose insulation (designated [shaded]).

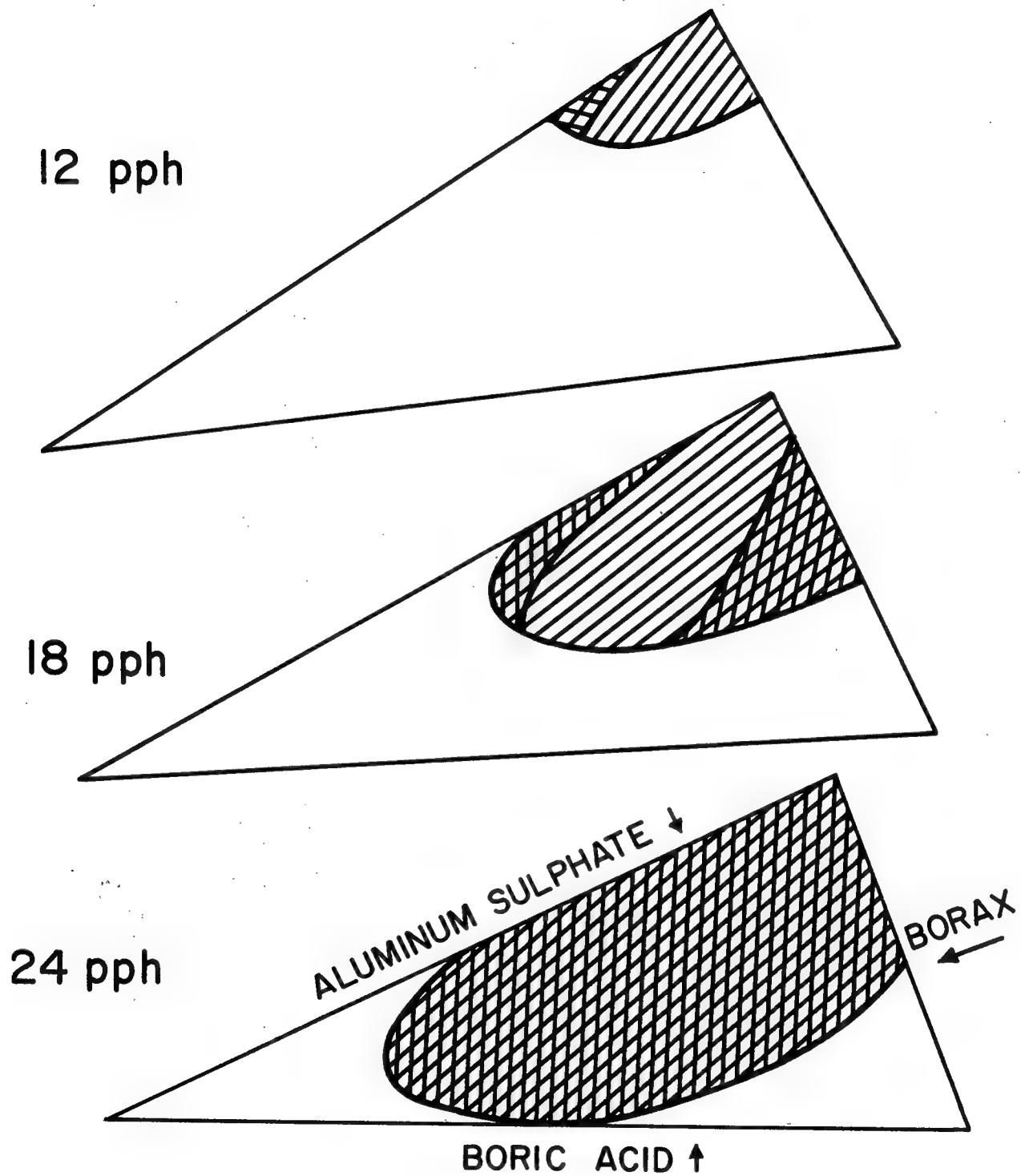



Figure 3. Formulations of borax, boric acid and aluminum sulphate capable of retarding both the smouldering and the flaming combustion of cellulose insulation (designated ).

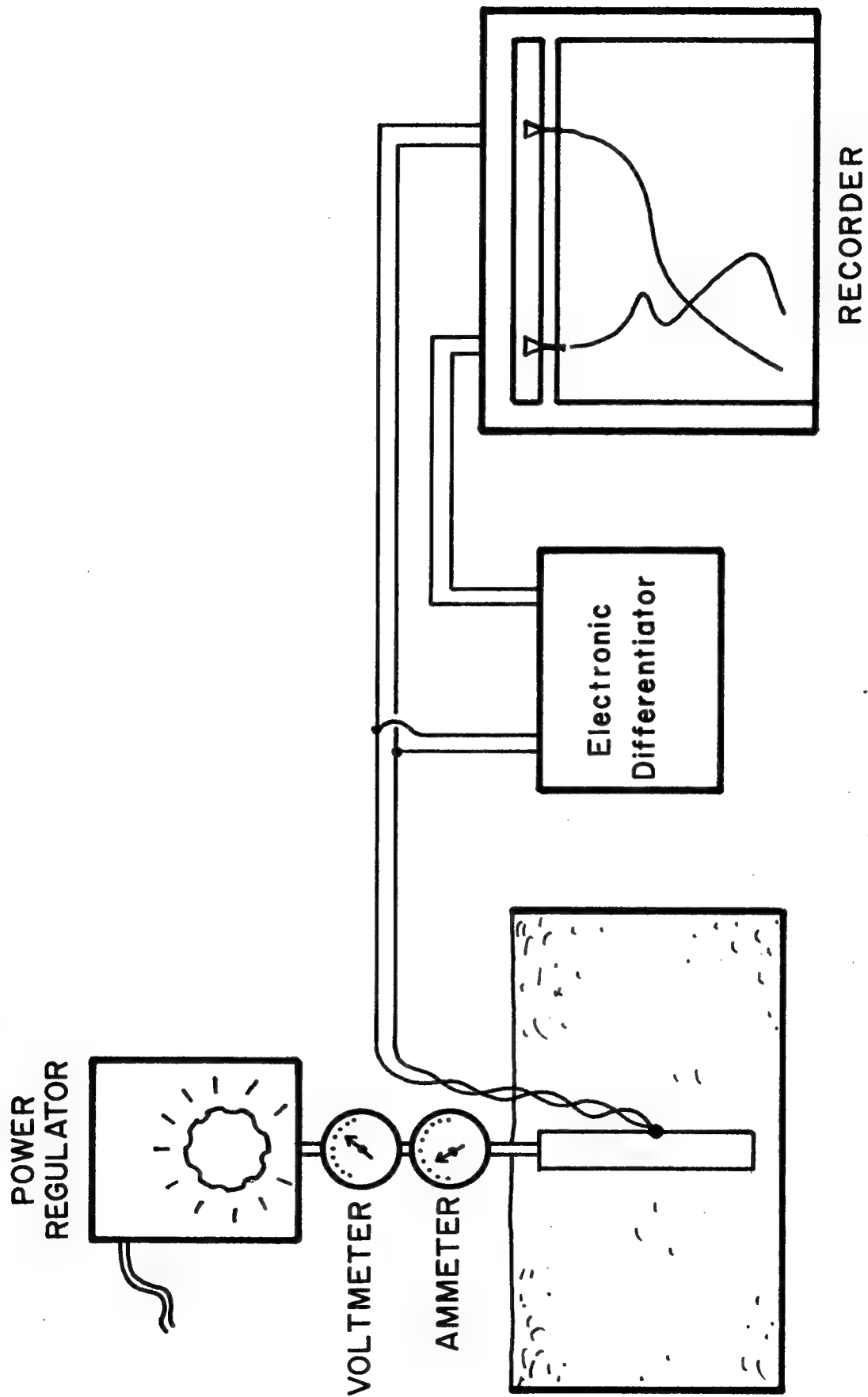


Figure 4. Schematic of electrical device to measure the smoulder resistance of cellulose insulation.

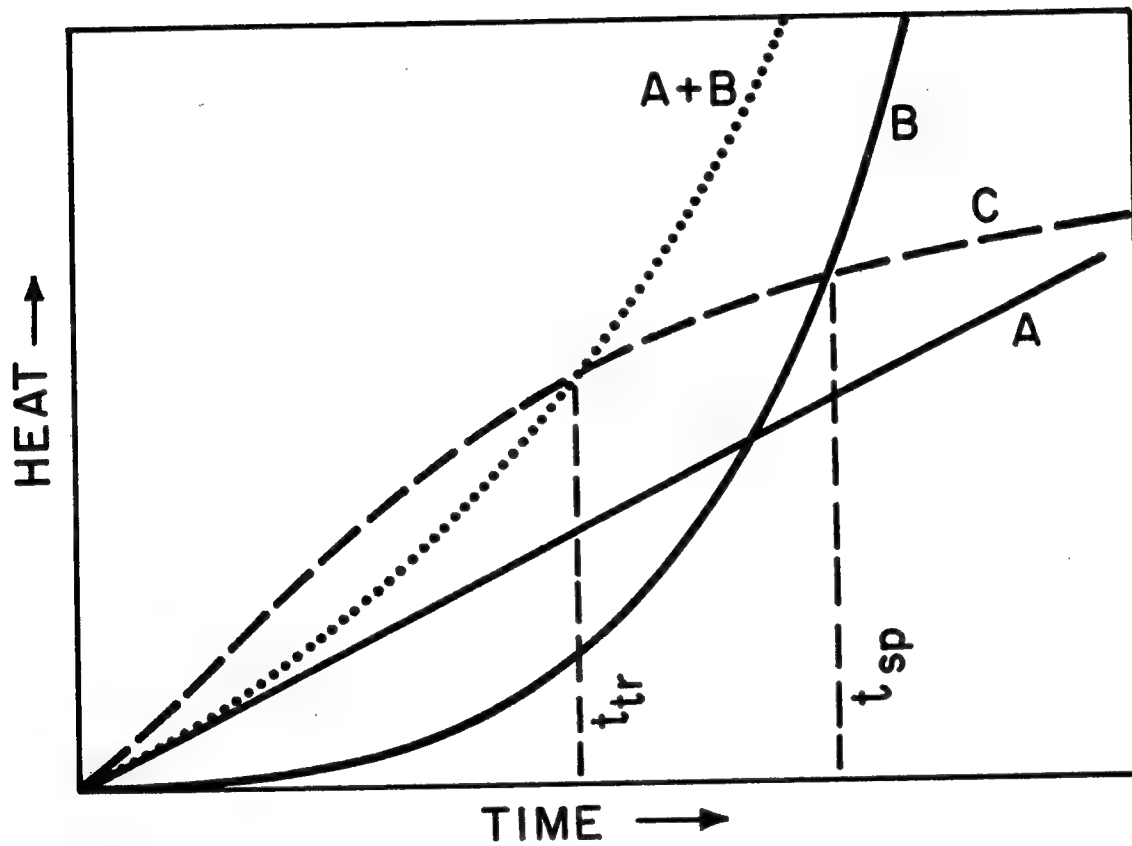


Figure 5. Heat energy balance as a function of time for cellulose insulation exposed to electrical ignition.

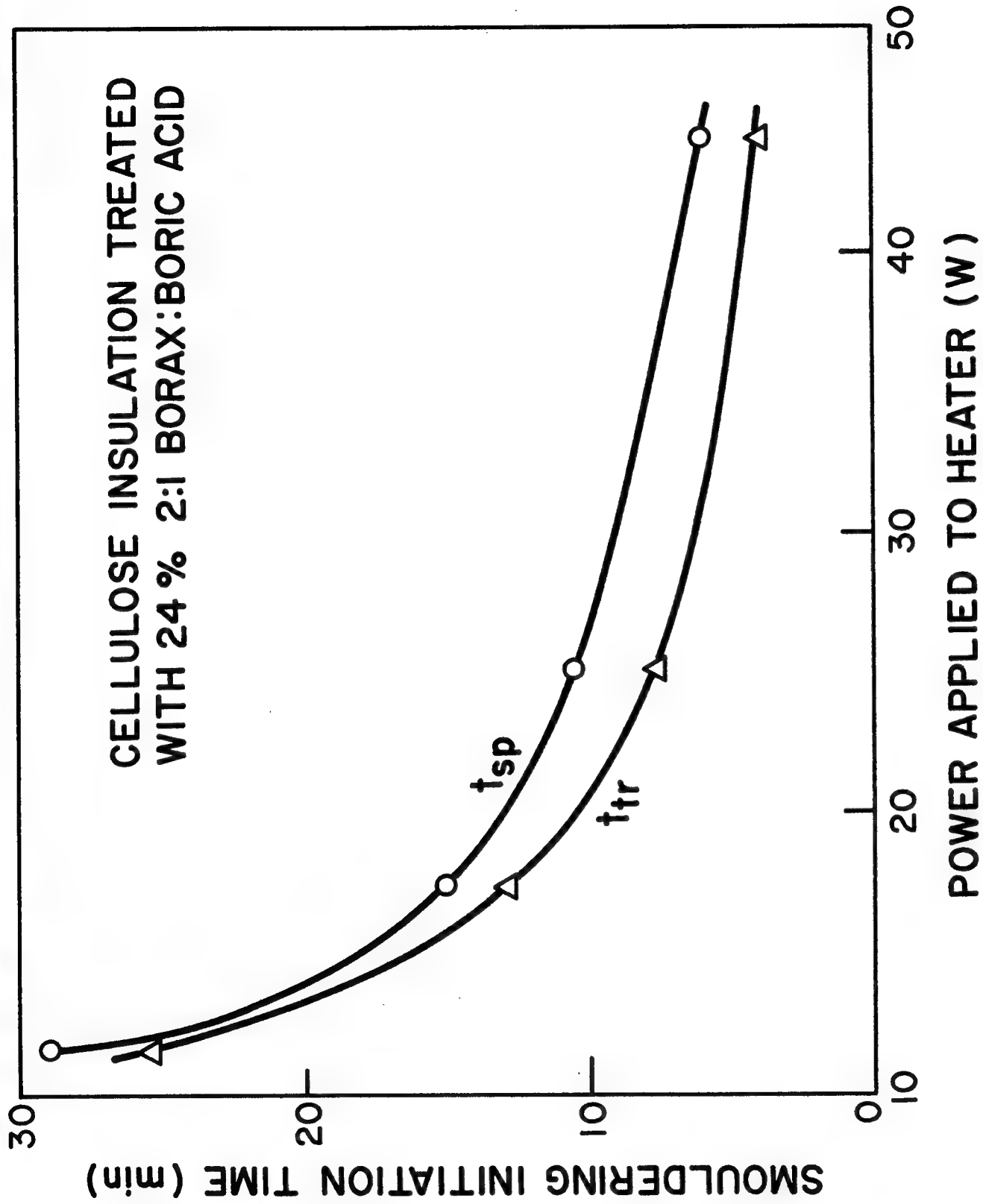


Figure 6. Time to initiate the smouldering combustion of cellulose insulation treated with 24% 2:1 borax:boric acid as a function of power supplied to the heater.

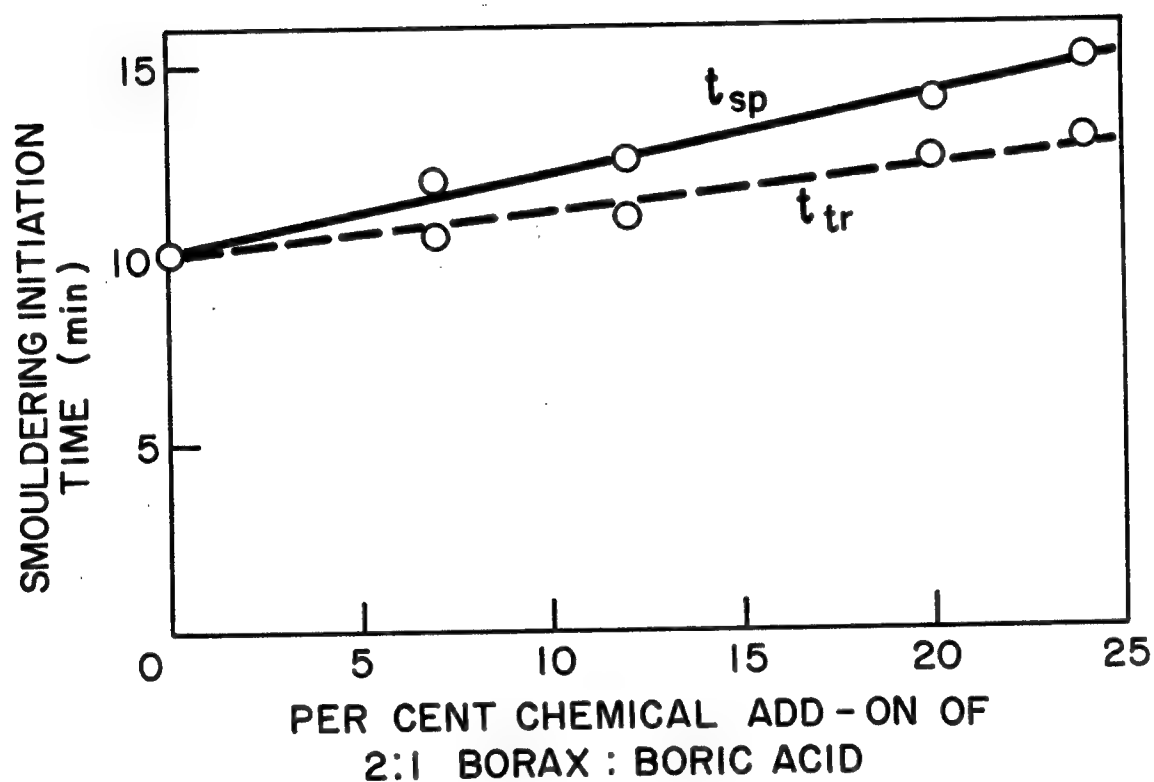


Figure 7. Time to initiate smouldering combustion (t_{sp} —; t_{tr} ---) as a function of chemical add on of a 2:1 borax:boric acid formulation.

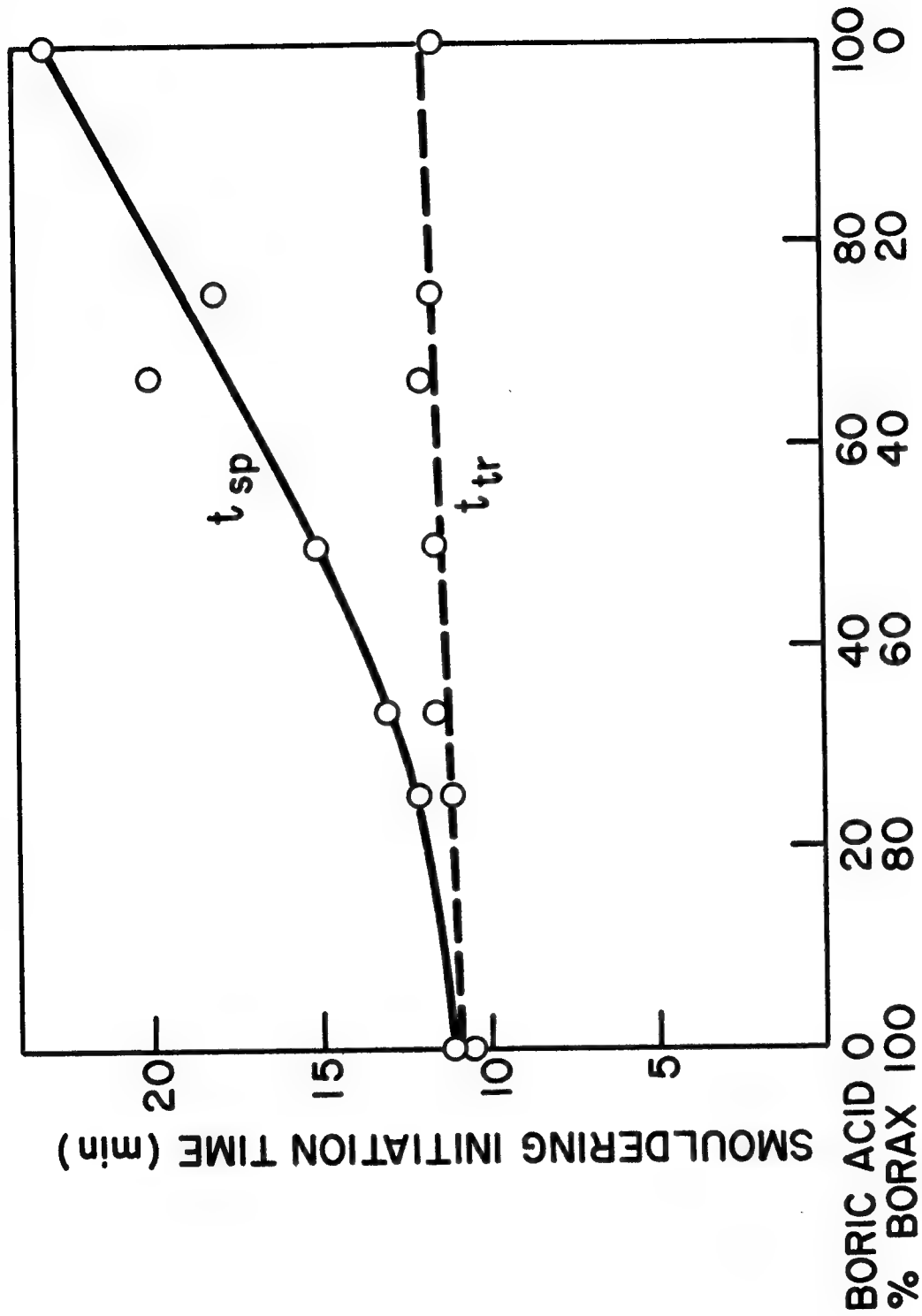


Figure 8. Time to initiate smouldering combustion (t_{sp} —; t_{tr} ---) as a function of borax:boric acid ratio when applied to cellulose insulation at a fixed treatment level of 20%.

CONSUMER RESEARCH ON FURNITURE FLAMMABILITY¹

by

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Introduction

This study was done in collaboration with the Bureau of Home Furnishings, California Department of Consumer Affairs. The study was undertaken as part of a larger project on California consumers' preferences for and problems with upholstered furniture. Special emphasis was given to assessing consumer knowledge and opinions of factors associated with furniture flammability for the following reasons:

1. The extent of involvement of furniture in fires in the United States. The National Electronic Injury Surveillance System (NEISS) report for February 1978, using data from hospitals with emergency treatment units, estimates that the number of injuries associated with upholstered furniture were 32,983 for the previous year (7). In a more recent article dealing specifically with fatal fires, National Fire Protection Association data are presented on leading ignition scenarios for 4,493 one- and two-fatality United States fires, 1971-1978. In the 18 leading scenarios, accounting for 52.6 percent of the deaths, 20.5 percent of the deaths were associated with ignition of upholstered furniture (2).
2. The indications in previous studies (1,3) that even relatively well educated consumers are generally naive with respect to flammability issues in general and legislation in particular. Consequently, they may act in ways counterproductive to their own well-being.
3. The controversy over the mandatory national flammability standard proposed by the Consumer Product Safety Commission. It has been suggested that such a standard may actually be a disservice to consumers in several ways. For example, there might be a restriction in cover fabrics available for purchase. At a recent hearing concerning the proposed flammability standard, industry and consumer representatives contended that the standard would eliminate approximately half of today's upholstery fabrics, including many popular cotton ones. Another concern was that costs for what is available would increase (5). California provides a natural testing area for questions about consumers' responses to flammability standards; a California upholstered furniture flammability standard has been in effect from October 1975 to March 1976 and again from March 1977 to the present time.

¹Partial support for this research was provided by a grant from the Kellogg Public Service Research Program, Division of Extended Learning, University of California, Davis.

Methodology

Two thousand questionnaires were mailed to California consumers in 20 counties selected by the probability-proportional-to-size method (6). Half of this sample was chosen to receive a consumer education booklet including a section on furniture fire facts. General information about household furniture was adapted from material provided by the Furniture Industry Consumer Advisory Panel. The fire information was collected and edited with the help of personnel at the Bureau of Home Furnishings and the Division of Textiles and Clothing.

Results

A total of 536 completed questionnaires were returned by the cut-off date. Analysis of these responses indicated that most respondents were aware that the majority of fire deaths in the United States occur in the home (Table 1). This question was asked to determine whether the general public might have a false sense of security in the home since the bulk of the publicity on fires deals with large fires in public places. Apparently, however, the majority of respondents were aware that the home is the most hazardous location.

Other flammability questions elicited fewer accurate responses. The majority of respondents did not know that California has an upholstered furniture flammability standard and of those who did, the majority thought resistance to burning by smoldering objects was the only requirement (Table 2). At present, the mandatory standard covers smoldering and flaming combustion of the filling material and flaming combustion of the fabric.

When asked which type of fabrics are more apt to burn, celluloseics such as linen, cotton, and rayon or synthetics such as nylon, polyester and polypropylene, 46% chose synthetics and 36% chose celluloseics (Table 3). Unfortunately, these responses are difficult to interpret because it is not known whether respondents were thinking of flaming or smoldering combustion and one-sided or two-sided ventilation of the fabric.

The majority of respondents admitted they could not evaluate the flame resistance of upholstered furniture by examining it (Table 4). These data run counter to the suggestion that consumers are now so well informed that they no longer need to be educated or protected with respect to furniture flammability.

The data presented in Table 5 suggest there is little direct relationship between what consumers know and what they think they know. Again, however, these data must be interpreted with caution since it is not known what type of combustion respondents were considering.

Another item asked for an opinion about flammability standards for upholstered furniture. As shown in Table 6, the majority of respondents thought there should be mandatory standards established by government. Following in popularity were voluntary standards by industry; only a few respondents thought there should be no standards.

A significant relationship was found between perceived ability to judge the flammability of furniture and opinion on standards (Table 7). A higher percentage of respondents who were confident of their ability to judge furniture flammability, compared to those less sure of their ability, felt there was no need for a standard; a higher percentage of the former group also selected mandatory standards. The important fact to note, however, is that at all three levels of perceived ability, approximately twice as many respondents wanted mandatory standards as desired voluntary or no standards.

Data on acceptance of possible effects of various types of standards are presented in Table 8. The most popular choice was flame retardant finishes on fabrics. The reaction against flame retardant finishes seems to have abated with the removal of TRIS from the market and subsequent decline in publicity concerning finishes. Only 18% of the sample said that an increase in cost would be acceptable.

Table 9 shows the frequency distribution of maximum acceptable increases in cost of furniture reported by respondents. The figure most often given was 10%, followed by 5%.

Another concern that arises when legislation is considered as a means to reduce fire hazards is the average length of time the items to be covered by regulations are retained in the household. Number of furniture fires can be expected to decline only as older, more hazardous items are replaced with newer, safer ones. Table 10 indicates the median ages of oldest/only furniture items in the respondents' households. Based on these data, one can observe that it will take a number of years for the full impact of changes in furniture flammability regulations to be realized.

After considering legislation, the next concern was the probable effectiveness of consumer education.

In California, the mass media carried a number of reports on furniture fires following the Bay Area Rapid Transit fire in January, 1979. In spite of this publicity, flammability was a relatively unimportant issue for the respondents who planned to purchase upholstered furniture during the following year. As shown in Table 11, characteristics given highest priority by furniture customers were comfort, durability, style, color and fabric material; over 75% of the respondents rated these characteristics as very important. Less than 50% of the respondents rated flammability as very important.

Data presented in Table 12 indicate that the majority of respondents felt their own experience was the most helpful source of information regarding furniture purchases. Only seven checked manufacturers' booklets.

This tendency to rely on one's own experience may in part be responsible for the apparent ineffectiveness of the consumer information booklet. As shown in Table 13, the booklet did not improve scores on the information questions in the questionnaire. (It should be noted that respondents were not asked if they had read the booklet in an effort to keep the situation as natural as possible. Such a question might have prompted them to check the booklet when they would not have done so otherwise. Also, since

there is a tendency for consumers to over-estimate the extent to which they try to keep informed, the validity of such data would have been questionable.)

The same analyses were run for only those respondents who intended to purchase at least one piece of upholstered furniture within the next year. It was thought that people who intended to buy furniture in the near future would probably be more receptive to a furniture information booklet. However, results were similar to those found for the total sample; there were no significant differences in responses to the information questions.

In an effort to understand how to improve consumer education, questionnaire data were analyzed to determine those variables that were related to concern about furniture flammability. Multiple regression analysis of the questionnaire data, presented in Table 14, suggested that three variables were of importance; smoking filtered cigarettes, income, and having a fire escape plan.

To determine the significance of each of these variables independent of the others, chi square analyses were computed. These analyses indicated that smoking filtered cigarettes was significantly related to concern about furniture flammability; respondents with a smoker in the household were more apt to be concerned (Table 15). Having a fire escape plan approached significance; those having an escape plan were less apt to be concerned (Table 16).

Although income showed only a tendency to be related to concern about flammability (Table 17), subsequent interviews suggested that income, or at least the buying of expensive furniture, may be an important variable. These interviews were conducted with 100 upholstered furniture customers in 18 stores in northern California. The stores were selected to represent high, middle and low price points.

When customers were asked to state, without prompting, important features in the item(s) they were looking for, only one person mentioned flammability. When asked what information should be included in an information booklet for consumers, five people mentioned flammability.

In response to the question, "Do you ask about flammability when shopping for furniture," 15 said yes and 83 said no; 2 did not answer this question. The reasons for these responses are given in Table 18. Having a smoker in the home was the reason most often given for asking about flammability. Lack of awareness of flammability as a concern with respect to upholstered furniture was the reason most often given for not asking. Some misinformation was also apparent in responses such as, "I assume I'm protected because I buy expensive furniture," and "I don't have to worry about fires because there are no smokers in the home."

Recommendations

The results of this research are important to consider in taking action to reduce fire hazards. As Schmitt and Dardis (4) have noted, consumers who are in ignorance of product hazards may underevaluate the benefits of

attempting to reduce the risks. Apparently, consumers are becoming aware of the flammability hazards associated with smoking cigarettes. However, many seem to be relatively unaware or unconcerned about hazards associated with other ignition sources.

Also, certain types of misinformation need to be corrected. Consumers should not assume that buying expensive furniture automatically insures fire protection. Neither should they assume that relative fire resistance is unimportant because it is relative. Perhaps more emphasis needs to be given to the fact that a few extra minutes of escape time often means the difference between life and death.

Many consumers have indicated a desire for furniture flammability standards, either mandatory or voluntary. Whatever means are used to protect the consumer, complacency should not be encouraged. It should be made clear that "fire resistant" is not equivalent to "fire proof" and consumers must not assume that the existence of standards excuses them from exercising reasonable precautions with respect to potential sources of fire hazards.

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Table 1
Opinions Regarding Location of Greatest Proportion
of Fire Deaths in United States

| Location | N | % |
|--------------------------|-----|------|
| Homes | 455 | (87) |
| Residential institutions | 26 | (5) |
| Public assemblies | 8 | (2) |
| Transportation | 6 | (1) |
| Stores, offices | 3 | (1) |
| Schools | 2 | (-) |
| Other | 2 | (-) |
| Combination | 20 | (4) |

Table 2
Distribution of Responses to California Upholstered
Furniture Flammability Standard Item

| Responses | N | % |
|----------------------|-----|----|
| a No standard | 235 | 53 |
| b Resists smoldering | 162 | 36 |
| c Resists open flame | 26 | 6 |
| d Cannot burn | 4 | 1 |
| e b and c | 16 | 4 |
| f b, c and d | 2 | - |
| g Other answers | 2 | - |

Table 3
Type of Fabric Thought More Apt to Burn

| Fabric | N | % |
|-------------|-----|------|
| Cellulosics | 187 | (36) |
| Synthetics | 244 | (46) |
| Don't know | 96 | (18) |

Table 4

Opinions Regarding Ability to Judge Flammability
of Upholstered Furniture

| Frequency of feeling able to judge | N | % |
|---------------------------------------|-----|------|
| Always | 8 | (2) |
| Often | 17 | (3) |
| Sometimes | 108 | (20) |
| Rarely or never | 398 | (75) |

Table 5

Chi Square Analysis of Perceived Ability to Judge Furniture Flammability
by Responses to Fabric Flammability Question

| | Can Judge | | | | | |
|------------------|--------------------|------|-----------|------|--------------------|------|
| | Always or Often | | Sometimes | | Rarely or Never | |
| More Apt to Burn | N | (%) | N | (%) | N | (%) |
| Cellulosics | 11 | (46) | 41 | (46) | 135 | (43) |
| Synthetics | 13 | (54) | 48 | (54) | 182 | (57) |

$$\chi^2 = .4 \quad p = \text{NS}$$

Table 6
Preference Regarding Flammability Standards
for Upholstered Furniture

| Type of standard desired | N | % |
|--------------------------|-----|------|
| Mandatory by government | 304 | (58) |
| Voluntary by industry | 184 | (35) |
| No standards | 18 | (3) |
| Other answer | 12 | (2) |
| Combination | 10 | (2) |

Table 7
Chi Square Analysis of Perceived Ability to Judge Furniture Flammability
by Preference for Furniture Flammability Standards

| Type of Standard | Can Judge | | | | | |
|------------------|-----------------|------|-----------|------|-----------------|------|
| | Always or Often | | Sometimes | | Rarely or Never | |
| | N | (%) | N | (%) | N | (%) |
| Mandatory | 17 | (71) | 62 | (62) | 225 | (59) |
| Voluntary | 3 | (13) | 35 | (35) | 145 | (38) |
| No standard | 4 | (17) | 3 | (03) | 11 | (03) |

$$\chi^2 = 18.07 \quad p < .01$$

Table 8
Acceptable Effects of Actions Taken
to Reduce Furniture Fires^a

| Effect | N | % |
|-----------------------------|-----|------|
| Flame retardant finishes | 404 | (75) |
| Limitation of cover fabrics | 79 | (15) |
| Increase in cost of items | 94 | (18) |
| None of the above | 62 | (12) |

^aMultiple responses allowed

Table 9
Maximum Acceptable Increase In Cost

| Maximum Percent | N | (%) |
|--------------------------|----|-----|
| 1 | 3 | 4 |
| 2 | 5 | 6 |
| 3 | 3 | 4 |
| 5 | 15 | 19 |
| 8 | 2 | 3 |
| 10 | 32 | 42 |
| 12 | 1 | 1 |
| 15 | 4 | 5 |
| 20 | 7 | 9 |
| 25 | 2 | 3 |
| 30 | 1 | 1 |
| 100 | 1 | 1 |
| Whatever is necessary | 1 | 1 |

Table 10

Median Age of Oldest/Only Furniture Items

| Item | Median |
|-------------------|--------|
| Upholstered chair | 9.5 |
| Ottoman | 8.5 |
| Rocking chair | 8.4 |
| Sofa | 7.6 |
| Sofa bed | 6.5 |
| Recliner chair | 5.7 |

Table 11

Importance of Various Characteristics
in Selecting Upholstered Furniture^a

| Characteristics | Very Important N (%) | Somewhat Important N (%) | Not Important N (%) | Mean Rating of Importance |
|------------------|-------------------------|--------------------------------|------------------------|------------------------------|
| Comfort | 184 (92) | 15 (8) | 2 (1) | 1.09 |
| Durability | 165 (84) | 29 (15) | 3 (1) | 1.17 |
| Style | 154 (80) | 33 (17) | 5 (3) | 1.22 |
| Color | 152 (76) | 44 (22) | 3 (2) | 1.25 |
| Fabric material | 137 (72) | 52 (27) | 2 (1) | 1.29 |
| Colorfastness | 120 (64) | 59 (31) | 10 (5) | 1.41 |
| Fabric finish | 116 (60) | 68 (35) | 8 (4) | 1.43 |
| Ease of cleaning | 107 (55) | 78 (40) | 11 (6) | 1.51 |
| Guarantee | 113 (58) | 63 (33) | 18 (9) | 1.51 |
| Price | 94 (48) | 96 (49) | 6 (3) | 1.55 |
| Frame material | 95 (50) | 79 (42) | 16 (8) | 1.58 |
| Flammability | 92 (48) | 71 (37) | 28 (15) | 1.66 |
| Frame finish | 85 (45) | 82 (43) | 23 (12) | 1.67 |

^aBased on subgroup of respondents who intended to purchase upholstered furniture during the following 12 months

Table 12
Most Helpful Source of Information
Regarding Furniture Purchase

| <u>Source</u> | <u>N</u> |
|-----------------------------|----------|
| My own experience | 160 |
| Store displays | 52 |
| Friends' experience | 28 |
| Salesperson | 26 |
| Interior designer | 16 |
| Newspaper ads | 13 |
| Magazine articles | 12 |
| Booklets from manufacturers | 7 |
| Magazine ads | 4 |
| TV & radio ads | 2 |
| Newspaper articles | 1 |
| TV & radio programs | 1 |
| Other | 21 |

Table 13

Cross-tabulation of Responses to Furniture Information Questionsby Receipt of Consumer Information Booklet

| Guarantees and Warranties | | | Type of Fabric More apt to Burn | | |
|---------------------------|---------------------|------------------|---------------------------------|---------------------|------------------|
| | No booklet N (%) | Booklet N (%) | | No booklet N (%) | Booklet N (%) |
| All mfrs. | 26 (15) | 23 (13) | Cellulosics | 101 (37) | 86 (34) |
| Some mfrs. | 121 (69) | 112 (66) | Synthetics | 126 (46) | 118 (47) |
| No mfrs. | 29 (16) | 35 (21) | Don't know | 49 (18) | 47 (19) |

California Upholstered Furniture Flammability Standard

| | No Booklet N (%) | Booklet N (%) |
|-----------------------|---------------------|------------------|
| a. No standard | 128 (55) | 107 (50) |
| b. Resists smoldering | 82 (35) | 80 (37) |
| c. Resists open flame | 13 (6) | 13 (6) |
| d. Cannot burn | 0 (-) | 4 (2) |
| e. b and c | 8 (3) | 8 (4) |
| f. b, c and d | 1 (-) | 1 (-) |
| g. Other answer | 1 (-) | 1 (-) |

Table 14

Multiple Regression of Selected Variables on
Importance of Furniture Flammability

| Independent Variables | R | r | Beta Weight | F ^a |
|--------------------------------------|-----|------|-------------|----------------|
| Smoke filtered cigarettes | .18 | -.18 | -.23 | 4.86 * |
| Income | .23 | .12 | .17 | 2.69 |
| Fire escape plan | .26 | .11 | .13 | 2.03 |
| Lighter fluid in home | .28 | .03 | .12 | 1.48 |
| Smoke detector in home | .29 | -.08 | -.08 | .83 |
| Fireplace in home | .30 | .01 | -.06 | .37 |
| Smoke pipe | .30 | -.09 | -.06 | .38 |
| Marital status | .30 | .01 | -.03 | .11 |
| Misuse of electric blanket | .30 | -.01 | -.02 | .08 |
| Smoke cigars | .30 | -.06 | .04 | .11 |
| Smoke unfiltered cigarettes | .31 | -.03 | -.02 | .03 |
| Fire extinguisher in home | .31 | -.03 | -.01 | .03 |
| Use of substances causing drowsiness | .31 | -.02 | -.01 | .02 |
| Handicapped persons in home | .31 | -.01 | -.01 | .01 |

^aObserved F values at completion of equation

* p < .05

Table 15
Chi Square Analysis of Importance of Furniture Flammability
by Smoking Filtered Cigarettes

| <u>Importance</u> | <u>Smoker in Household</u> | | | |
|--------------------|----------------------------|------|-----|------|
| | No | | Yes | |
| | N | (%) | N | (%) |
| Very important | 40 | (40) | 47 | (56) |
| Somewhat important | 40 | (40) | 30 | (36) |
| Unimportant | 19 | (19) | 7 | (8) |

$\chi^2 = 6.34 \quad p = .04$

Table 16
Chi Square Analysis of Importance of Furniture Flammability by Fire Escape Plan

| <u>Importance</u> | <u>Fire Escape Plan</u> | | | |
|--------------------|-------------------------|------|-----|------|
| | No | | Yes | |
| | N | (%) | N | (%) |
| Very important | 65 | (49) | 22 | (44) |
| Somewhat important | 52 | (40) | 16 | (32) |
| Unimportant | 14 | (11) | 12 | (24) |

$\chi^2 = 5.27 \quad p = .07$

Table 17

Chi Square Analysis of Importance of Furniture Flammability by Income

| Importance | Income | | |
|-------------------------------|---------------------------|------------------------|-------------------------|
| | \$24,999 or less N (%) | 25,000-39,999 N (%) | 40,000 or more N (%) |
| Very important | 50 (54) | 27 (47) | 10 (31) |
| Somewhat important | 29 (31) | 24 (41) | 15 (47) |
| Unimportant | 14 (15) | 7 (12) | 7 (22) |
| $\chi^2 = 5.84 \quad p = .21$ | | | |

Table 18

Responses to Item on Asking about Flammability When Shopping for Furniture

| Ask | | Do Not Ask | |
|------------------------|----------|--------------------------|----------|
| Reasons | N | Reasons | N |
| Smoker(s) in the home | 7 | Had not thought about it | 42 |
| Child(ren) in the home | 4 | No children in the home | 7 |
| Miscellaneous | <u>4</u> | Unconcerned | 6 |
| TOTAL | 15 | Assume protection | 6 |
| | | Know about regulations | 5 |
| | | No smokers in the home | 5 |
| | | Everything burns | 4 |
| | | Careful | 3 |
| | | Miscellaneous | <u>5</u> |
| | | TOTAL | 83 |

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FIREFIGHTER REACTION TO FIRE FATALITIES

Abstract: Firefighters are engaged in a high risk profession in which they are likely to encounter individuals who have died as a result of fires. This study presents the results of a survey involving 35 firefighters.

Introduction

Firefighters are engaged in a high risk profession where their lives are frequently threatened and where they may at some point discover an individual who has died at the scene of a fire. This study was done to identify how firefighters deal with the difficult experience of encountering a person who has died at a fire. In addition, the study sought to determine the most frequent responses of firefighters to the discovery of a victim. The possibility of the responses being affected by the age, sex or appearance of the victim was also analyzed. The most frequent responses were examined to determine if they fit the criteria of healthy long term coping mechanisms.

Limits of the Study

1. The questionnaire suggests some of the responses of firefighters after discovering a dead body at the scene of a fire. The list may not be all-inclusive, therefore all possible responses were not necessarily considered.
2. The study does not seek to differentiate between discoveries of dead victims for the first time as opposed to subsequent discoveries.
3. The study will utilize any firefighters who have at some time discovered a dead body at the scene of a fire, with no limit placed on the time that has elapsed since that discovery. The study is thus dependent on individual recall.
4. No limit was placed on the age or rank of the firefighters who responded to this questionnaire.
5. The researchers acknowledge that they cannot control the effect of individual variation of responses to stress in this study.

DEFINITIONS OF TERMS

Crispy Critter

An individual who has been burned beyond recognition.

Stress

Perception of a thing, situation, ect., as a threat to an individual's personal integrity.

Responses

Feelings experienced by the firefighter and/or behaviors utilized by firefighters after the discovery of a dead body at the scene of a fire.

Firefighters

Those individuals engaged in the profession of promoting fire safety through fighting fires and meeting the needs of the public in emergency situations.

Coping Mechanisms

Activities utilized by individuals in order to reduce the perceived threat in a stress situation.

ASSUMPTIONS IN THE STUDY

1. The discovery of a dead body at the scene of a fire constitutes a stressful event for the firefighter.
2. Firefighters respond in some way to the discovery of a dead body at the scene of a fire.
3. Responses listed in the questionnaire comprise a thorough list of how firefighters respond after the discovery of a dead body at the scene of a fire.
4. Certain parameters such as the age of the firefighter, and the number of victims discovered may have an effect on the responses of firefighters to the discovery of a dead body at the scene of a fire.
5. The nature of the firefighter's profession is such that many will at some point in their career discover a dead body at the scene of a fire.
6. Respondents will accurately respond to all items of the questionnaire to the best of their recollection.

UNDERLYING THEORY

Basic theory underlying this study was that which relates to psychological stress, stress related to death and dying, and coping mechanisms. There are numerous definitions of what is meant by psychological stress, a simple one stating that psychological stress is related to cognitive

factors leading to the evaluation of threat (Monat (1) 1977:12). In other words, it is the perception of a situation as a threat to one's survival or personal integrity (Wallace (2) 1978:458. Gerald Caplan (3) discusses stress and mental health. If the crisis or stressful life event is managed by effective coping, the individual strengthens his emotions and problem-solving ability. In the process new coping behaviors are learned and assimilated. Equilibrium and maintenance of wellness are thus dependent on the nature of the stress and/or the person's coping mechanisms ((3) 1964:137,143).

The concept of death as a threatening event is discussed by Kubler-Ross in her book *Death - The Final Stage of Growth* (4). In it she points out that "death has become a dreaded and unspeakable issue to be avoided by every means possible in our modern society" ((4) 1975:5. She points out that death reminds humans of their vulnerability in spite of modern technology, that it is indiscriminate and inescapable. Death is frightening, death is unfamiliar, and it will always be hard for people to accept ((4) 1975:5-6). Becker aptly sums up what Kubler-Ross is saying with the following statement, "...that of all things that move man, one of the principal ones is his terror of death" ((5) 1977:310).

For every stress, there is a recommended way to cope (U.S. News 1978:81). Kolb (7) describes the need for adapting to stress in the following manner. "Since adaptation is the very essence of life, it is not strange that man, the most highly developed species, has evolved ...psychological devices, which assist him in dealing with emotional needs and stress. These devices, help him meet the needs for affection, personal security, personal significance and defense against perturbing affects. By acting without conscious recognition on man's part, such devices effect adaptation to inner situations and experiences that would otherwise be sorely, even intolerably troublesome" ((7) 1977:85).

Coping behaviors must also be recognized as highly individualistic since the perception and interpretation of, and particularly the defenses against threat remain sufficiently varied between humans to give a panorama of responses (Katz (8) 1977:241). Lazarus also found this to be true as he notes that cognitive process determine the quality and intensity of an emotional reaction, and thos process also underlie the selection and use of coping activities ((9) 1977:145).

THE REVIEW OF THE LITERATURE

A review of the literature by the researchers revealed no studies identical to this one, nor did it reveal any studies of a population similar to the one in this research effort. Some studies on coping with stress and with death are to be found in the literature, and are described below.

Janice Bell (10) completed a study on stressful life events and coping methods in mental -illness and -wellness behaviors. In her study, two groups of coping mechanisms were studied, long and short-term strategies. Long-term coping methods include constructive, realistic ways of coping

with stress that can effectively relieve stress for long periods of time. Long-term coping mechanisms include; talking it out with others (friend, relative, professional), trying to find out more about the situation, believing in a supernatural power, physical exercise, taking some definite action on the basis of the individual's present understanding, drawing on past experience, and making several alternate plans for handling the situation ((10) 1978:137).

Short-term coping mechanisms are defined by Bell as those which reduce stress and tension temporarily, but which carried on for long periods of time do not deal with reality. Short-term coping mechanisms include; drinking alcoholic beverages, daydreaming, trying to see humorous aspects of the situation, not worrying because everything will work out, using food and food substances, getting prepared to expect the worst, cursing, using drugs, becoming involved in other activities to keep one's mind off the problem, and crying ((10) 1978:1357).

Meninger (11) also identified several ways people cope with stress. He listed: food and food substitutes, use of alcoholic beverages, laughing or crying or cursing, boasting, sleeping, talking it out, thinking through including rationalization, physical exercise, acting to alter the situation, pointless overactivity, fantasy-formation, and daydreaming ((11) 1963:146).

Kolb cites a study by Janis in which a study was done by Janis on immediate reactions to acute stress of different kinds (12). Janis found that obsessional staring is an initial response to a disaster, as observers are preoccupied by thoughts and fantasies about what might have happened to them during the disaster, or what might happen in the future ((12) 1977:534). This is similar to Millerd's description of death imprint, where survivors are confronted with their own death through witnessing the death of others ((13) 1977:35). Thus it is reasonable to believe that firefighters, as observers and/or survivors, must deal with feelings surrounding the discovery of dead victims.

The researchers looked at initial responses of individuals to loss because of these factors. One of these responses was described by Millerd as psychic numbing. This is defined as an attitude of indifference or lack of feeling in the health professional's behavior as he/she tends to the needs of the dying person ((13) 1977:35). This is similar to Miller's description of intellectual acceptance of death, where the person experiencing the loss shows little or no emotion ((14) 1978:75).

Robert Plank and others describe the initial reactions to a sudden death as shock. This reaction has two components. The first is denial ((15) 1969:205). Miller explains the importance of denial when she points out that the sudden death may be too much for the psyche, and the individual may choose to deny or "shut off" feelings which acknowledge the reality of death ((14) 1978:75).

The second component of the shock reaction as described by Plank is depersonalization or "emotional anesthesia." He described this as a sense of detachment which acts as a defense against anxiety ((15) 1969:205).

Other more immediate responses to death were discussed by Miller in her study of how survivors cope with the trauma of sudden death. She describes guilt, where the survivor wonders if he somehow contributed to the death, and anger, which reflects the helplessness and frustration the person is feeling ((14) 1978:76).

The suddenness of the death has an effect on how persons react to that loss. Quint's study of how nursing students cope with death showed that lack of awareness of impending death is a condition which increases the possibility of a shock response should death unexpectedly take place ((16) 1967:150). Janis's study, as cited by Kolb, echoes this finding in that he found that the more sudden the stressful event, the more profound is the individual's response ((12) 1977:534). If the firefighter does not expect to discover a dead body, it is increasingly probable that he will experience more intense feelings subsequent to the discovery.

Other factors affect the magnitude of these responses to death. Quint believes that the psychological effects of these experiences are directly related to the dimensions of familiarity -- unfamiliarity with death and adequate-inadequate performance in the presence of death ((16) 1967:60). Miller expands on these findings when she points out that nurses consider death a defeat, and that the sudden loss of a patient generates feelings of helplessness. Nurses are forced to acknowledge their lack of control in preventing death ((14) 1978:71). Janis found that the more opportunity the individual had to anticipate the fear of the event and work through the "worrying" about the threat to himself, the more reality tested the individual's self-reassurances are likely to be, and the more emotional control he is likely to exhibit under actual stress ((17) 1977:274).

To summarize, numerous methods of adapting to stress, both for long and short periods, have been identified in the literature. Actual research studying the response of firefighters to the discovery of a dead body at the scene of a fire apparently has not been done previously. Due to the fact that witnessing and confronting death has been found to produce anxiety, hence the need for adaptation in individuals, initial responses to unexpected death were explored. Factors affecting the intensity of response to an unexpected stress were also reviewed.

THE RESEARCH METHODOLOGY

The procedure utilized in this study was the administration of a questionnaire to firefighters who at some point in their career discovered a dead body at the scene of a fire. A review of the literature provided some studies on how individuals cope with stress-inducing situations, and these studies were utilized as a foundation for the composition of the questionnaire in this study.

The questionnaire was pretested on a sample of fifteen firefighters who at some point in their career discovered a dead body at the scene of a fire. Subsequent to the pretest, changes were made in the terminology of two questions and in the directions preceding the questions. The firefighters were given the opportunity to answer open-ended questions which attempted to more effectively elicit all possible responses to finding a dead victim. However, the firefighters did not write in any responses other than those asked about in the actual questionnaire.

After necessary changes were made in the questionnaire, the Chief of Public Education and Internal Control of the San Francisco Fire Department was contacted in order to determine which fire stations most frequently respond to fires where a person may have been killed. Once this information was obtained questionnaires were taken to those same fire stations and distributed to all firefighters at the station. This procedure was continued until a total of thirty-five completed questionnaires were obtained.

THE QUESTIONNAIRE

The questionnaire was compiled by the researchers utilizing studies on coping mechanisms in response to stress as a foundation. Five firefighters were talked to prior to the construction of the questionnaire in an attempt to elicit coping responses particular to firefighters when faced with the stress of discovering a dead victim.

The questionnaire was pretested on a sample of fifteen firefighters to determine clarity of terminology and any additional responses the firefighters may have experienced subsequent to finding a dead person who has died at a fire.

Necessary changes were made in format and terminology. No additional responses were included in the questionnaire as none were elicited by the pretest sample. At this point the questionnaire was determined suitable for administration to the study sample.

SAMPLING PROCEDURE

This study is concerned with a very specific population of firefighters, i.e., those who have discovered a dead body at the scene of a fire. The authors felt that administering their questionnaire to those firefighters who have not discovered a dead body would not be useful to the purpose of the study. Therefore, the researchers determined, with the help of the Chief of the Division of Public Education and Internal Control, those fire stations where the firefighters are more likely to have discovered a dead victim at a fire. Each of these fire stations house from five to fifteen firefighters. The researchers distributed questionnaires to forty firefighters at these stations. A total of thirty-five completed questionnaires were returned. The limitation placed on the sample was that all respondents had to have discovered a dead victim at the scene of a fire.

COLLECTION PROCEDURE

After deciding which fire stations to visit, and securing permission from the fire department to visit any fire stations necessary, the researchers went to the recommended fire stations in order to distribute the questionnaire. At each station the officer of the day was contacted, and he was asked to distribute questionnaires to all firefighters present at the station. He was asked to explain to the potential respondents that two nursing students from U.S.F. were interested in determining how firefighters respond to the particular stress situation, and that the study was being done to complete graduation requirements. The questionnaires were filled out by the firefighters immediately at each of the three stations visited by the researchers. Ten days were needed in order to visit the three firestations and amass thirty-five completed questionnaires.

TREATMENT OF THE DATA

The analysis of the data consisted of determining how frequently every response was utilized by the firefighters. Frequency of response was also studied in terms of the age of the firefighters and the number of victims discovered by the firefighters.

In addition, the mean, mode and range were determined for the following data: age and rank of the firefighters, number of years spent in the fire department, whether the firefighter had children or not, and the number of victims discovered by the firefighters.

Finally, a scattergram was constructed to determine the nature of the correlation between the age of the firefighter and the length of time spent as a member of the fire department. This scattergram exhibited a strong positive correlation. Hence, the correclation coefficient was determined in order to discover the exact strength of the relationship between the two variables.

RESULTS OF THE STUDY

The data used in the study included: the subject's age, length of time in the fire department, rank, whether the subject had children or not, the number of victims discovered by the subject and their approximate ages.

A total of thirty-five firefighters were sampled. The ranks of the subjects are as follows: twenty-five firefighters, six lieutenants, three captains and one battalion chief.

The ages of the subjects in the study ranged from twenty-five to fifty-four years old. The mean age for the group was thirty-seven and four tenths years of age, while the modes were thirty-six and thirty-eight years old.

Through the construction of a frequency scattergram, a positive

correlation was found to exist between the age of the subject and length of time in the fire department. The numerical correlation coefficient was determined to be ninety-six one hundredths.

Length of time working in the fire department ranged from two tenths of a year to twenty-nine years. The mean number of years in the fire department was twelve and four tenths years while the median number of years was ten, and the modes were ten and twelve years.

This questionnaire seeks to investigate emotions and/or behaviors of firefighters after they have discovered a person who has been killed at the scene of a fire. The questions below offer possible responses of a firefighter following the discovery of a fire victim(s). To the best of your recollection, please answer ALL of the following questions as they relate to your own personal experience. If the question does not apply to your experience, please check the column marked not applicable. Some questions have several items listed below them, please answer each item by checking the appropriate box. Thank you for your time and cooperation.

Biographicla Data:

Age: _____

Length of time in the fire department: _____

Rank: _____

Do you have children of your own? _____

1. In your career as a firefighter, approximately how many victims have you discovered? _____
2. To the best of your recollection, what were their approximate ages?

| | | Always Frequently Sometimes Never Not Applicable | | | | |
|----|---|--|--|--|--|--|
| | | | | | | |
| 3. | How often do you feel an in- crease of feelings? | | | | | |
| 4. | How frequently do you feel the sex of the victim in- fluenced your response/ feelings? | | | | | |

5. If the victim is burned beyond recognition, i.e. crispy critter,

Always Frequently Sometimes Never Not Applicable

- a. how frequently do you think about the crispy critter more than the person who has died as a result of smoke inhalation?

5a.

- b. how frequently do you think about the crispy critter less than the person who has died as a result of smoke inhalation?

5b.

6. Do you attempt to resuscitate the victim(s) of smoke inhalation if he/she is:

- a. 0-2 years old

6a.

- b. 3-7 years old

b.

- c. 8-12 years old

c.

- d. 13-20 years old

d.

- e. 21-40 years old

e.

- f. 41-60 years old

f.

- g. 61 years old or older

g.

7. If resuscitation was attempted and was unsuccessful, does the death have a greater impact on you in terms of:

- a. your feelings of sadness

7a.

- b. a sense of failure

b.

- c. a sense of anger

c.

8. While at the scene of a fire, after you have discovered a victim, how frequently:

Always Frequently Sometimes Never Not Applicable

a. do you experience feelings of helplessness at being unable to save a person's life?

8a.

b. does the performance of tasks at the scene of a fire enable you to put the victim out of your thoughts?

b.

c. do you experience nausea due to the discovery of the victim?

c.

d. do you refer to the victim using a nickname or label, i.e., crispy critter?

d.

e. do you cry?

e.

f. do you want to cry?

f.

g. do you scream?

g.

h. do you curse?

h.

i. do you break out in a cold sweat?

i.

j. do you pray?

j.

k. do you get angry at the circumstances that directly lead to the death, i.e. carelessness, poverty, ignorance?

k.

l. do you make jokes?

l.

m. do you laugh at jokes even when you don't feel they're funny?

m.

9. At any time after leaving the scene of a fire where you have discovered a victim, how

| frequently do you: | | Always | Frequently | Sometimes | Never | Not Applicable |
|---|-----|--------|------------|-----------|-------|----------------|
| a. want to discuss the discovery with anyone? | 9a. | | | | | |
| b. discuss the discovery with another firefighter? | b. | | | | | |
| c. discuss the discovery with friends? | c. | | | | | |
| d. discuss the discovery with a clergyman? | d. | | | | | |
| e. discuss the discovery with a bartender? | e. | | | | | |
| f. discuss the discovery with a family member? | f. | | | | | |
| g. feel the desire to drink alcohol if it was permissible in your job? | g. | | | | | |
| h. feel the desire to take drugs? | h. | | | | | |
| i. go out and jog/run? | i. | | | | | |
| j. throw or break something? | j. | | | | | |
| k. wish to be alone and avoid others? | k. | | | | | |
| 10. How frequently do you experience a reluctance to respond to the next call for a working fire? | 10. | | | | | |
| 11. Do you ever consider leaving the fire department after discovering a fire victim? | 11. | | | | | |

Additional data revealed twenty six of the subjects had children of their own while the remaining nine had no children. Firefighters who had children, as well as those who did not, answered with the same frequency to item three of the questionnaire that the ages of the victim influenced the intensity of their response/feelings.

The approximate number of victims discovered ranged from one to fifty.

The mean number of victims discovered was eleven and seven-tenths, while the mode was five.

The approximate ages of the victims was not considered to be an important parameter of this study because the majority of the respondents were unable to accurately estimate the ages of their victims. Typical responses included "infants to old age" or "adults."

For the remainder of the results, the reader is referred to the tables included in this research report. The following is a discussion of the findings significant to the researchers as revealed in the tables.

A study of Table 1 revealed that age of the victim was an important variable influencing the intensity of the subject's response to the discovery of a dead victim. On the other hand, Table 2 indicated that sex as a variable was less influential than age was in determining the intensity of the subject's response.

Table 1. Responses to Item Three of the Questionnaire

| Question Three | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|-------------------|--------|-----|------------|----|-----------|----|-------|----|----------------|---|
| | No.* | %** | No. | % | No. | % | No. | % | No. | % |
| | 13 | 37 | 5 | 14 | 11 | 31 | 6 | 17 | 0 | 0 |

Number and frequency to all responses to Item Three

* No. indicates number of responses. Total number of responses to each item of the questionnaire was thirty-five.

** % indicates percentage of firefighters frequency of response to each item of the questionnaire.

Table 2. Responses to Item Four of the questionnaire

| Question Four | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|------------------|--------|---|------------|---|-----------|----|-------|----|----------------|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| | 13 | 6 | 1 | 3 | 12 | 34 | 17 | 49 | 3 | 9 |

Number and frequency of all responses to Item Four.

A review of the results compiled for Question Five revealed that a slightly greater percentage of firefighters thought about the crispy critter more than the person who had died as a result of smoke inhalation. Apparently the appearance of the victim has an effect on the firefighters' response, as indicated in Table 3.

Table 3. Responses to Item Five of the Questionnaire

| Question Five | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|------------------|--------|----|------------|----|-----------|----|-------|----|----------------|----|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| 5a. | 4 | 11 | 4 | 11 | 14 | 40 | 9 | 26 | 4 | 11 |
| 5b. | 1 | 3 | 2 | 6 | 13 | 37 | 15 | 40 | 4 | 11 |

Number and frequency of all responses to Item Five

Table 4 clearly shows that an overwhelming majority of firefighters will attempt to resuscitate the victim of smoke inhalation regardless of their age. An interesting exception was noted for one respondent who had discovered victims only between the ages of thirteen and eighty. He indicated that he would frequently attempt resuscitation for the victims between ages thirteen and sixty, and he would sometimes attempt resuscitation for the victim over sixty years old. This individual stood out as he was the only respondent who did not indicate that he would always resuscitate all victims, and that he would attempt to resuscitate older victims less frequently than younger victims. Speculation as to why he answered in this manner is beyond the scope of this discussion.

Table 4. Responses to Item Six of the Questionnaire

| Question Six | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|-----------------|--------|----|------------|---|-----------|---|-------|---|----------------|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| 6a. | 33 | 94 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 |
| 6b. | 33 | 94 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 |
| 6c. | 33 | 94 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 |
| 6d. | 33 | 94 | 1 | 3 | 0 | 0 | 0 | 0 | 1 | 3 |
| 6e. | 33 | 94 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 |
| 6f. | 33 | 94 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 |
| 6g. | 33 | 94 | 0 | 0 | 1 | 3 | 0 | 0 | 1 | 3 |

Number and frequency of all responses to Item Six of the Questionnaire.

Table 5 revealed that the most frequent response of firefighters to unsuccessful resuscitation was a feeling of sadness. Senses of failure and anger were also experienced, but less frequently than the feeling of sadness.

Table 5. Responses to Item Seven of the Questionnaire

| Question Seven | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|-------------------|--------|----|------------|----|-----------|----|-------|----|----------------|----|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| 7a. | 6 | 17 | 14 | 40 | 9 | 26 | 5 | 14 | 1 | 3 |
| 7b. | 1 | 3 | 2 | 6 | 17 | 49 | 13 | 37 | 2 | 6 |
| 7c. | 1 | 3 | 2 | 6 | 12 | 34 | 15 | 43 | 5 | 14 |

Number and frequency of all responses to Item Seven of the questionnaire.

Responses of firefighters to the discovery of a dead body at the scene of a fire are recorded in Table 6. The more frequently occurring responses include: a feeling of helplessness at being unable to save a person's life, the performance of tasks at the scene of a fire in order to put thoughts of the victim out of his mind, anger directed at the circumstances that lead to the death, nausea upon discovery of the victim, and the utilization of nicknames such as crispy critter when referring to the victim. Also evident in the Table are those responses that rarely occur when a firefighter discovers a victim at the scene of a fire. These responses include: breaking out in a cold sweat, crying, and screaming. A response interesting to the researchers was that while few firefighters responded that they cried after the discovery of a victim, a large number indicated that they wanted to cry. Some of the firefighters apparently suppressed certain feelings after discovering a dead body at the scene of a fire.

Later responses of firefighters to the discovery of a dead body at the scene of a fire are compiled in Table 7. One hundred percent of the subjects responded that at least some of the time they discuss the discovery of a dead body with another firefighter. This is the only response in the questionnaire that did not elicit a frequency of never. Other commonly occurring responses include: the desire to discuss the discovery with someone, the discussion of the discovery with a family member, and the discussion of the discovery with friends. It seems clear to the researchers that firefighters feel a need to verbalize feelings about discovering a dead body with another individual. There is a marked decrease in the frequency of the other responses to the discovery of a dead body at the scene of a fire. The most infrequent responses include: discussing the discovery with a clergyman, feeling the desire to take drugs, and throwing or breaking something.

Table 8 and 9 reveal that the majority of firefighters do not feel a reluctance to respond to the next call for a working fire, nor do they consider leaving the fire department after discovering a dead body. An outstanding exception noted by the researchers was one subject who responded never to the majority of questions in items eight and nine. However, he indicated that he always felt a reluctance to respond to the next call for a working fire and he also always felt a desire to leave the fire department after discovering a dead victim.

Table 6. Responses to Item Eight of the Questionnaire

| Question Eight | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|-------------------|--------|---|------------|----|-----------|----|-------|----|----------------|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| 8a. | 3 | 9 | 7 | 20 | 22 | 63 | 3 | 9 | 0 | 0 |
| 8b. | 3 | 9 | 10 | 29 | 16 | 46 | 5 | 14 | 1 | 3 |
| 8k. | 0 | 0 | 10 | 29 | 18 | 51 | 7 | 20 | 0 | 0 |
| 8c. | 0 | 0 | 0 | 0 | 22 | 63 | 12 | 34 | 1 | 3 |
| 8d. | 2 | 6 | 6 | 17 | 14 | 40 | 12 | 34 | 1 | 3 |
| 8h. | 3 | 9 | 4 | 11 | 13 | 37 | 15 | 43 | 0 | 0 |
| 8m. | 1 | 3 | 2 | 6 | 15 | 43 | 16 | 46 | 1 | 3 |
| 8l. | 1 | 3 | 2 | 6 | 13 | 37 | 19 | 54 | 0 | 0 |
| 8f. | 1 | 3 | 0 | 0 | 14 | 40 | 20 | 57 | 0 | 0 |
| 8j. | 2 | 6 | 1 | 3 | 9 | 26 | 23 | 66 | 0 | 0 |
| 8i. | 0 | 0 | 0 | 0 | 6 | 16 | 29 | 83 | 0 | 0 |
| 8e. | 1 | 3 | 0 | 0 | 2 | 6 | 32 | 91 | 0 | 0 |
| 8g. | 1 | 3 | 0 | 0 | 1 | 3 | 33 | 94 | 0 | 0 |

Number and frequency of all responses to Item Eight. Responses listed in order of those most commonly utilized by firefighters. Frequency of utilization was determined by the total of the always, frequently and sometimes responses.

Included in the review of the data was a division of the responses based on the ages of the firefighters and the number of victims discovered by the firefighter. A regrouping of the data based on the ages

Table 7. Responses to Item Nine of the Questionnaire

| Question Nine | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|------------------|--------|----|------------|----|-----------|----|-------|----|----------------|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| 9h. | 5 | 14 | 13 | 37 | 17 | 49 | 0 | 0 | 0 | 0 |
| 9a. | 2 | 6 | 9 | 26 | 19 | 54 | 5 | 14 | 0 | 0 |
| 9f. | 0 | 0 | 2 | 6 | 23 | 66 | 9 | 26 | 1 | 3 |
| 9c. | 1 | 3 | 4 | 11 | 20 | 57 | 10 | 29 | 0 | 0 |
| 9k. | 0 | 0 | 1 | 3 | 9 | 26 | 25 | 71 | 0 | 0 |
| 9g. | 3 | 9 | 2 | 6 | 5 | 14 | 24 | 69 | 1 | 3 |
| 9e. | 2 | 6 | 0 | 0 | 7 | 20 | 26 | 74 | 0 | 0 |
| 9i. | 2 | 6 | 2 | 6 | 4 | 11 | 25 | 71 | 2 | 6 |
| 9j. | 2 | 6 | 1 | 3 | 4 | 11 | 27 | 80 | 1 | 3 |
| 9h. | 1 | 3 | 2 | 6 | 0 | 0 | 31 | 89 | 1 | 3 |
| 9d. | 0 | 0 | 0 | 0 | 2 | 6 | 31 | 89 | 2 | 6 |

Number and frequency of all responses to question nine.
Responses listed in order of those occurring at some time,
including all always, frequently and sometimes responses.

Table 8. Responses to Item Ten of the Questionnaire

| Question Ten | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|-----------------|--------|----|------------|---|-----------|---|-------|----|----------------|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| | 4 | 11 | 0 | 0 | 1 | 3 | 29 | 83 | 1 | 3 |

Number and Frequency of all responses to Item Ten

Table 9. Responses to Item Eleven of the Questionnaire

| | Always | | Frequently | | Sometimes | | Never | | Not Applicable | |
|--|--------|---|------------|---|-----------|---|-------|----|----------------|---|
| | No. | % | No. | % | No. | % | No. | % | No. | % |
| | 2 | 6 | 0 | 0 | 1 | 3 | 31 | 89 | 1 | 3 |

Number and Frequency of all responses to Item Eleven

of the subjects, revealed findings felt by the researchers to be of significance to the study. One such example was found with the firefighters aged forty-five to fifty-five. These men used nicknames, such as crispy critter, much less frequently than did those aged twenty-five to forty-five.

Further view of the data revealed one hundred percent of the firefighters aged twenty-five to thirty-five never cried, yet thirty-three percent expressed a desire to cry. The older firefighters differed in that some of them utilized crying as a response when they discovered a dead body. Some of these men expressed a wish to cry as well as reporting that they sometimes would cry when they discovered a dead body.

Another interesting difference was noted in the data in that those aged forty-five to fifty-five showed a slightly less frequent tendency to experience feelings of anger upon discovering a dead victim. It is the opinion of these researchers that perhaps the older firefighters experienced less anger due to their more frequent exposure to dead victims.

Still several more differences were noted in the forty-five to fifty-five year old firefighters. These men joked about the victims significantly less than the younger men. In addition, they responded less frequently to the items that related to discussing the finding of a victim. The veteran firefighters discussed the discovery of a victim with friends and family less than the younger firefighters. Once again, the researchers hypothesize that due to their increased experiences of discovering victims, older firefighters feel a decreased need to talk about the discovery.

The researchers also sought to determine whether the number of victims discovered by the firefighters affected their responses as elicited by items eight and nine of the questionnaire. While some of the responses were unaffected by the number of victims discovered, the researchers found some noticeable differences in the frequency of some of the other answers. These differences were as follows: the more victims discovered, the less frequently firefighters were inclined to refer to victims by nicknames such as crispy critter, the less frequent was the desire to cry, the less frequent were feelings of anger on the part of the firefighter, and less frequent was the desire to laugh at jokes. When there was a change in the frequency of response, it seemed to consistently be that when a firefighter discovered more victims, his response was less intense.

Responses of firefighters after leaving the scene of the fire where they have discovered a dead body were also affected by the number of victims discovered. The more victims discovered by the firefighter, the less frequently did the firefighter want to talk about the discovery, and the less frequently did the firefighter discuss the discovery with friends, a bartender or his family. The number of victims discovered did not significantly affect the frequency of other responses. These firefighters apparently did not feel such a strong need to talk about their discoveries.

INTERPRETATIONS

After compiling the frequencies of the firefighters' responses, the following reactions were found to be the most commonly occurring. Common reactions after leaving the scene of a fire included talking to another firefighter about the discovery of a victim, and discussing the discovery with friends or family. Frequent responses of firefighters at the scene of a fire include: feelings of helplessness at being unable to save the victim, the performance of tasks which distract the firefighter from thoughts of the victim, feelings of anger at the circumstances that lead directly to the death, and experiencing nausea subsequent to the discovery of the victim.

Firefighters' frequent practice of discussing the discovery of a victim with another person reflects the use of a long term coping mechanism as defined by Janice Bell. The firefighters' overwhelming use of this strategy indicates to the researchers that firefighters utilize healthy coping mechanisms which allow them to deal with stress over long periods of time. The researchers feel a possible explanation for firefighters' common use of discussion of the discovery may be that they recognize the benefits of sharing their feelings with others. Through this practice, firefighters dissipate stress which enables them to function efficiently in their roles as firefighters.

The researchers believe that the feelings of helplessness and anger experienced by firefighters at the scene of a fire may reflect feelings of inadequacy. The following quote by Kastenbaum offers a possible explanation for such a sense of inadequacy. He states that "...failure to help the helpless when one is able to do so makes that person partially responsible" ((18) 1977:321). Because of a sense of professionalism, firefighters may feel that they should save everyone. Hence, when failure occurs, firefighters feel angry and helpless.

Nausea may occur either due to the grotesque appearance of the victim or because of the effects of noxious gases at the scene of a fire.

The performance of tasks at the scene of a fire enables firefighters to put thoughts of the victim out of their mind. The use of this response resembles a short term mechanism as defined by Bell (10). Since this study has substantiated firefighters' effective use of long term coping mechanisms, the authors feel the performance of distracting tasks may represent a temporary means of coping with the discovery. This distraction allows them to function capably until such time when discussion of the discovery is possible.

This study also found that the older the firefighter was and the more victims discovered at the scene of a fire, the less intense and emotional were his responses. This finding seems to substantiate Janis' study which states that the more opportunity the individual has to anticipate an event and work through the worrying involved, the more reality-based is his response ((17) 1977:274). Thus the researchers feel that firefighters are

more able to deal with discovering persons who have died with less disturbance in their emotional equilibrium after having experienced the event several times, than are those firefighters who have only experienced the discovery infrequently.

This section represents the researchers interpretation of why particular responses occurred frequently.

IMPLICATIONS FOR NURSING

Firefighters and nurses experience a high degree of stress in the performance of their jobs. Both continuously face the possibility of dealing with death. The researchers feel that firefighters deal with this situation in a healthy manner through their discussions subsequent to the discovery of a dead victim. These authors feel that nurses might effectively cope with the death of their patients through similar discussions. Perhaps the organization of peer discussion groups would facilitate verbalization of stressful feelings concerning death.

Dealing with the discovery of a dead victim is difficult. While firefighters seem to be coping with the stress well, nurses should be aware of their vulnerability as a high risk group. Principles of primary health prevention dictate that community health nurses, in conjunction with the fire department, assess the ongoing needs of this population. If necessary, nurses should be available to facilitate stress reducing intervention should the firefighters' system of coping ever falter.

RECOMMENDATIONS FOR FURTHER RESEARCH

The researchers feel that a study similar to this one should be carried out for other vulnerable groups. Some possible groups are policemen, paramedics, and emergency medical technicians.

A second recommendation of these researchers is that studies similar to this one be conducted with firefighters in other cities to determine universality of the responses.

Still another recommendation to consider is the administration of this questionnaire immediately after the discovery of a dead victim and again after a specific period of time has lapsed, i.e. ten days, in order to minimize the variable effects of recall.

The authors also feel that further research on coping mechanisms and death should be carried out in order to more accurately define healthy strategies for coping with death as a stress-inducing situation.

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FIRE SAFETY EVALUATION OF MATTRESSES FOR PENAL INSTITUTIONS

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ABSTRACT

Eight mattress cushioning materials were subjected to five different fire test procedures to evaluate their suitability for use in penal institutions. This paper presents the results of this study.

SUMMARY AND CONCLUSIONS

This study, performed under contract for the California Department of Corrections, indicates the flammability characteristics of eight mattress cushioning materials. These materials are candidate materials for use in penal institutions, and were subjected to five different fire test protocols.

The test materials included five polyurethane foam formulations (with and without combustion modifiers), a fire retardant cotton batting, a neoprene foam, and a fire retarded mixed fiber pad. Each material was evaluated by each test protocol both uncovered and covered with a uniform institutional mattress ticking material.

Whole mattresses or mattress halves were subjected to each of five test protocols of increasing severity which are believed to represent a cross section of ignition techniques used by penal institution inmates. A data record of each individual test was obtained which included measurements of temperature, smoke opacity, combustion products, and weight loss. In addition a video record of each test was obtained.

The following general and specific conclusions may be drawn from this study:

1. The severity of the test protocols, in increasing order of severity, appears to be: cigarette test, matchbook test, solvent test, newsprint test, roll-up test.
2. The cigarette test did not serve as a useful screening tool in this test series due to uniformly good performance of all test materials except the cotton batting.
3. All other test protocols did to some degree differentiate fire performance of materials, with dramatic differences in weight loss for many materials.
4. The roll-up test proved to be a very severe challenge to most materials. The combustion conditions generated by this test appeared to overpower the effects of most combustion modifiers and therefore did not provide the test sensitivity of other test procedures.
5. The newsprint test gave the widest spread in weight loss measurements, appeared to be the screening procedure of choice, and provided the best test sensitivity for this array of test materials.

6. The test cover fabric significantly influenced combustion characteristics of test materials as follows:

- (a) In low heat flux conditions (i.e. the cigarette and matchbook tests) the fabric acted as an effective barrier by preventing sustained combustion of any cushioning material.
- (b) As heat flux conditions increased the contribution of the fabric to test measurements increased. Maximum smoke opacity values for covered tests uniformly exceeded those obtained in uncovered tests, and for many materials weight loss was greater when covered by test fabric than the equivalent uncovered test.
- (c) In general, the presence of the cover tended to have a retarding effect on combustion, as indicated in average burn rate data which typically showed reduced burn rates of materials when covered.

7. All of the test protocols did serve the useful purpose of producing a test series of varying ignition conditions and severities. However, it would appear that not all of the procedures would be suitable for material evaluation under regulatory conditions. The cigarette and matchbook tests present very little challenge to most materials and would therefore not be suitable for screening purposes where it may be necessary to differentiate between a conventional material and one that is combustion modified. The roll-up test, although admittedly a severe challenge to materials and a useful technique to evaluating "state of the art" products, does appear to present the most difficulty in reproducibility of test conditions and consequently non-uniformity and non-reproducibility of test results. The internal diameter of roll-up cylinder, the width of the mattress, the tilt of the roll, the amount and conditioning of the test newspaper, the initial ignition point of the newspaper, would all appear to be critical factors that would require careful standardization.

8. For regulatory purposes it would appear that some form of a flammable solvent or newsprint test would represent the best choice as regards a screening technique and test reproducibility. Both procedures can be fairly easily standardized, appear to be reproducible, and do differentiate combustion characteristics between the presently available population of candidate materials.

9. In this test series the conventional non-fire-retardant polyurethane foam was the poorest performing material, and was totally consumed under all test conditions, except for cigarette tests and covered matchbook tests.

10. The addition of a combustion modifier to the conventional polyurethane foam did significantly improve the performance of the foam, particularly under low and moderate ignition flux conditions. As the severity of ignition condition increased the difference in performance between the F.R. and non-F.R. foam decreased, due to the test condition overpowering the retarding effect of the combustion modifier. However, even under the severest test protocol test data indicate a definite positive effect of the fire retardant system.

11. The materials of choice under this series of test conditions would appear to be the Hypol and neoprene foams. It is the authors' opinions that the Hypol foam was marginally better than the neoprene due to significantly better performance of Hypol under roll-up test conditions, and the pronounced tendency of neoprene to undergo periods of sustained smoldering in several of the tests.

12. In broad generalities the following would appear to summarize the combustion characteristics of each material in this study.

- (a) The non-F.R. and F.R. polyurethane foams ignited easily, readily supported flaming combustion, burned quite rapidly, did not smolder.
- (b) The Densite and high resiliency foams ignited less easily, supported flaming combustion, burned relatively slowly, did not smolder.
- (c) The F.R. cotton batting, mixed fiber pad, and neoprene, were difficult to ignite, did not readily support flaming combustion, burned very slowly, readily supported sustained smoldering.
- (d) The Hypol was very difficult to ignite, did not support flaming combustion, did not burn, supported extremely slow smoldering under one test condition.

13. It should be emphasized that this study reflects only on the combustion characteristics of the stated test materials under the described ignition test protocols. No account has been taken in this study of other important materials factors such as physical properties or economics, nor do these data necessarily reflect on material performance under other full scale test conditions. In addition, information is available to suggest that some of the materials included in this study are now available in "improved" versions. However, it is not possible to conjecture on how these improved materials would perform under similar test conditions.

14. It is apparent from the data generated in this study that a wide variety of materials, with a whole spectrum of flammability and physical properties, is available for use as penal institution mattresses. The material of choice will depend upon a number of factors, including: (a) cost, (b) level of fire performance desired (this will be related to the type of specific occupancy), and (c) comfort and physical properties.

15. Bedding products such as blankets and sheets were not included in this series because of the desire to reduce test variables to a minimum and to simplify test protocols as much as possible. However, it is felt that the inclusion of such products would not have altered the overall pattern of test results though the specific test measurements may have been modified.

MATERIALS RATING SYSTEM

Historical evidence has shown that attempts to rate materials in flammability tests are subject to great dangers. Numerous researchers have pointed out the tendency of ratings to change and even reverse as minor changes in or modifications to test procedures are studied. At best it would appear that flammability rating systems are arbitrary and are often based upon the researcher's individual preferences, weightings, and priorities rather than clearly established scientific principles.

However, the fire researcher in industry, government and academia is constantly asked to make judgements regarding the specific performance of materials, based upon his tests. Such questions as "what do you recommend?" or "what's the best material?" are the constant companion of those involved in material evaluation, as management and regulatory officials seek to find answers for pressing problems.

Consequently many researchers establish their priorities and guidelines for material evaluation and ratings based upon their expertise and knowledge of flammability testing and material performance.

Although aware of the problems, dangers, and criticisms of flammability rating systems, an attempt has been made to evaluate material performance in this study and to ascribe numerical ratings, based upon a 1 - 10 scale, to each material for specific test measurements in each test. The numerical rating system is shown in Table 1, and ratings of individual materials for each specific test are presented in Tables 2 to 5. Under this system materials with the lowest overall numerical ratings are considered to have been the best performers under the specific test protocol. Small differences in overall numerical ratings between materials should not be considered significant. However, large numerical differences probably do indicate significant difference in performance between materials. In addition, it is felt that this numerical rating system does give general guidance as to the relative flammability performance of each material under each specified test condition.

The ratings are not intended to represent recommendations or endorsements by the Bureau of Home Furnishings Flammability Research Laboratory of specific materials but are merely an attempt to report test results and measurements in a comparative non-technical manner.

Table 6 presents a summary ranking for each material, for four test procedures, uncovered and covered. The combined ranking for all 4 test procedures shows an overall ranking of materials as follows:

| RANK | MATERIAL |
|------|----------------------|
| 1 | Hypol |
| 2 | Neoprene |
| 3 | Cotton Batting |
| 4 | Fiber Pad |
| 5 | Densite |
| 6 | High Resiliency Foam |
| 7 | FR - PU |
| 8 | PU |

TABLE 1. TEST RATING SYSTEM

| RATING | WEIGHT LOSS PERCENT | AVE. BURN RATE PERCENT/MIN. | MAX. TEMPS. °F | SMOKE OPACITY PERCENT | MAX. CORE TEMP. °F |
|--------|------------------------|--------------------------------|-------------------|--------------------------|-----------------------|
| 1 | 0-5 | 0-1 | 0-100 | 0-10 | 0-200 |
| 2 | 5-10 | 1-3 | 100-200 | 10-20 | 200-300 |
| 3 | 10-20 | 3-6 | 200-300 | 20-30 | 300-400 |
| 4 | 20-30 | 6-9 | 300-400 | 30-40 | 400-500 |
| 5 | 30-40 | 9-12 | 400-500 | 40-50 | 500-600 |
| 6 | 40-50 | 12-15 | 500-600 | 50-60 | 600-700 |
| 7 | 50-60 | 15-18 | 600-700 | 60-70 | 700-800 |
| 8 | 60-70 | 18-21 | 700-800 | 70-80 | 800-900 |
| 9 | 70-80 | 21-24 | 800-900 | 80-90 | 900-1000 |
| 10 | 80-100 | 24 | 900 | 90-100 | |

TABLE 2. MATERIAL RATING - MATCHBOOK TEST

MEASUREMENT

| MEASUREMENT | UNCOVERED | | | | | | | COVERED | | | | | | | | |
|--------------------|-----------|-------|----|---------|-------|----------|--------|-----------|----|-------|----|---------|-------|----------|--------|-----------|
| | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD |
| Weight Loss | 10 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Avg. Burn Rate | 6 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. 2 Ft. | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. 4 Ft. | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. Ceiling | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Smoke - Top | 10 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Smoke - Middle | 10 | 6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Smoke - Bottom | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max. Core Temp. | 10 | 8 | 2 | 2 | 1 | 2 | 4 | 3 | 5 | 4 | 2 | 2 | 1 | 2 | 1 | 4 |
| TOTALS | 53 | 35 | 10 | 11 | 9 | 10 | 12 | 11 | 13 | 12 | 11 | 10 | 9 | 10 | 9 | 12 |
| Combined Total | 66 | 47 | 21 | 21 | 18 | 20 | 21 | 23 | | | | | | | | |

no graph

TABLE 3. MATERIAL RATING - SOLVENT TEST

MEASUREMENT

| MEASUREMENT | UNCOVERED | | | | | | | | COVERED | | | | | | | |
|--------------------|-----------|-------|-----|---------|-------|----------|--------|-----------|---------|-------|----|---------|-------|----------|--------|-----------|
| | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD |
| Weight Loss | 10 | 9 | 3 | 1 | 1 | 1 | 1 | 1 | 10 | 10 | 4 | 2 | 1 | 1 | 1 | 1 |
| Avg. Burn Rate | 10 | 6 | 2 | 1 | 1 | 1 | 1 | 1 | 7 | 6 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. 2 Ft. | 10 | 8 | 10 | 7 | 3 | 3 | 4 | 3 | 10 | 6 | 3 | 5 | 5 | 2 | 3 | 3 |
| Max. Temp. 4 Ft. | 10 | 5 | 5 | 3 | 2 | 2 | 2 | 2 | 7 | 5 | 2 | 3 | 2 | 1 | 2 | 2 |
| Max. Temp. Ceiling | 10 | 5 | 4 | 2 | 2 | 2 | 2 | 2 | 6 | 5 | 2 | 3 | 2 | 1 | 2 | 2 |
| Smoke - Top | 10 | 10 | 10 | 10 | 7 | 8 | 9 | 10 | 10 | 10 | 10 | 10 | 10 | 4 | 10 | 10 |
| Smoke - Middle | 10 | 10 | 10 | 9 | 3 | 4 | 6 | 3 | 10 | 10 | 10 | 10 | 7 | 2 | 8 | 9 |
| Smoke - Bottom | 4 | 4 | 3 | 1 | 1 | 1 | 1 | 1 | 8 | 9 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max. Core Temp. | 10 | 10 | 10 | 10 | 2 | 7 | 7 | 8 | 10 | 10 | 10 | 10 | 10 | 10 | 6 | 10 |
| TOTALS | 84 | 67 | 57 | 44 | 22 | 29 | 33 | 31 | 78 | 71 | 43 | 45 | 39 | 23 | 34 | 39 |
| Combined Total | 162 | 138 | 100 | 89 | 61 | 52 | 67 | 70 | | | | | | | | |

TABLE 4. MATERIAL RATING - NEWSPRINT TEST

MEASUREMENT

| MEASUREMENT | UNCOVERED | | | | | | | COVERED | | | | | | | | |
|--------------------|-----------|-------|-----|---------|-------|----------|--------|-----------|----|-------|----|---------|-------|----------|--------|-----------|
| | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD |
| Weight Loss | 10 | 7 | 5 | 2 | 2 | 3 | 9 | 9 | 10 | 10 | 10 | 3 | 1 | 3 | 2 | 3 |
| Avg. Burn Rate | 8 | 4 | 2 | 1 | 1 | 1 | 1 | 2 | 5 | 4 | 2 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. 2 Ft. | 6 | 3 | 4 | 1 | 2 | 2 | 1 | 3 | 10 | 6 | 5 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. 4 Ft. | 4 | 2 | 3 | 1 | 2 | 2 | 1 | 2 | 6 | 3 | 2 | 1 | 1 | 1 | 1 | 1 |
| Max. Temp. Ceiling | 3 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 5 | 3 | 2 | 2 | 1 | 1 | 1 | 1 |
| Smoke - Top | 10 | 10 | 10 | 10 | 8 | 7 | 2 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Smoke - Middle | 9 | 9 | 10 | 9 | 5 | 3 | 1 | 9 | 10 | 10 | 10 | 10 | 8 | 9 | 8 | 9 |
| Smoke - Bottom | 2 | 5 | 6 | 6 | 1 | 1 | 1 | 1 | 9 | 9 | 8 | 5 | 1 | 2 | 1 | 5 |
| Max. Core Temp. | 10 | 10 | 10 | 8 | 5 | 6 | 10 | 10 | 10 | 10 | 10 | 6 | 2 | 9 | 3 | 8 |
| TOTALS | 62 | 52 | 52 | 39 | 28 | 27 | 27 | 48 | 75 | 65 | 59 | 39 | 26 | 37 | 28 | 39 |
| Combined Total | 137 | 117 | 111 | 78 | 54 | 64 | 55 | 87 | | | | | | | | |

TABLE 5. MATERIAL RATING - ROLL-UP TEST

| MEASUREMENT | UNCOVERED | | | | | | | COVERED | | | | | | | | |
|--------------------|-----------|-------|-----|---------|-------|----------|--------|-----------|----|-------|----|---------|-------|----------|--------|-----------|
| | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD | PU | FR-PU | HR | DENSITE | HYPOL | NEOPRENE | COTTON | FIBER PAD |
| Weight Loss | 10 | 10 | 10 | 10 | 1 | 6 | 10 | 10 | 10 | 10 | 10 | 10 | 3 | 6 | 6 | 10 |
| Avg. Burn Rate | 9 | 9 | 2 | 2 | 1 | 1 | 1 | 1 | 6 | 6 | 2 | 2 | 1 | 1 | 1 | 2 |
| Max. Temp. 2 Ft. | 10 | 10 | 10 | 10 | 5 | 2 | 1 | 2 | 10 | 7 | 4 | 7 | 4 | 2 | 2 | 4 |
| Max. Temp. 4 Ft. | | | | | | | | | | | | | | | | |
| Max. Temp. Ceiling | 9 | 6 | 5 | 5 | 3 | 2 | 1 | 2 | 8 | 6 | 4 | 5 | 4 | 2 | 2 | 4 |
| Smoke - Top | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Smoke - Middle | 7 | 10 | 10 | 10 | 1 | 9 | 5 | 7 | 10 | 10 | 10 | 10 | 9 | 9 | 9 | 10 |
| Smoke - Bottom | 1 | 10 | 10 | 8 | 1 | 1 | 1 | 1 | 2 | 3 | 10 | 1 | 1 | 1 | 8 | 2 |
| Max. Core Temp. | 6 | 10 | 10 | 10 | 1 | 6 | 10 | 10 | 2 | 10 | 10 | 10 | 1 | 7 | 4 | 10 |
| TOTALS | 62 | 75 | 67 | 65 | 23 | 37 | 39 | 43 | 58 | 62 | 60 | 55 | 33 | 38 | 42 | 52 |
| Combined Total | 120 | 137 | 127 | 120 | 56 | 75 | 81 | 95 | | | | | | | | |

TABLE 6. MATERIAL RANKINGS SUMMARYTEST PROCEDURES

| <u>MATERIAL</u> | <u>MATCHBOOK</u> | | <u>SOLVENT</u> | | <u>NEWSPRINT</u> | | <u>ROLL-UP</u> | | <u>COMBINED</u> |
|-----------------|------------------|---|----------------|---|------------------|---|----------------|---|-----------------|
| | UC | C | UC | C | UC | C | UC | C | |
| PU | 8 | 8 | 8 | 8 | 8 | 8 | 5 | 6 | 59 |
| FR-PU | 7 | 6 | 7 | 7 | 6 | 7 | 8 | 8 | 56 |
| HR | 2 | 5 | 6 | 5 | 6 | 6 | 7 | 7 | 44 |
| DENSITE | 4 | 3 | 5 | 6 | 4 | 4 | 6 | 5 | 37 |
| HYPOL | 1 | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 12 |
| NEOPRENE | 2 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 16 |
| COTTON | 6 | 1 | 4 | 2 | 1 | 2 | 3 | 3 | 22 |
| FIBER PAD | 4 | 6 | 3 | 3 | 5 | 4 | 4 | 4 | 33 |

TESTING AND APPLICATIONS OF PHOSPHORUS
BASED FLAME RETARDANTS IN PLASTICS

by

A. W. Morgan
D. S. T. Wang
T. C. Mathis

Chlorinated phosphates, chlorinated phosphonates, and organophosphates have found utility in a variety of polymers and plastic applications. Several polymers, including polyurethanes, poly(vinyl chloride), butadiene-acrylonitrile, and acrylics may be effectively modified by systems based on phosphorus. When flame retardancy is a criterion, efficient development of formulations has required a major effort in identifying testing and selection methods. A general method of developing flame retardant formulations is described and illustrated for several commercial applications. Current progress in evaluating proposed smoldering test parameters is reported.

THE IMPACT OF AN EXTERNAL POOL FIRE
ON AN INTACT AIRCRAFT FUSELAGE

BY

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Submitted for Presentation at the
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San Francisco, California

PURPOSE

The purpose of this paper is to summarize the results of recent NAFEC efforts as a representation of current knowledge of the interaction of external fuel fires with aircraft fuselages. The results are derived from three broad areas:

1. A C-133 fuselage exposed to fires up to 8 feet by 10 feet,
2. A DC-7 fuselage exposed to a 20-foot-square fuel fire, and
3. An array of model tests wherein scaled fuselages were subjected to a wide variety of fire conditions.

BACKGROUND

Aircraft fire safety efforts at the National Aviation Facilities Experimental Center (NAFEC) have in recent years emphasized the impact of external pool fires on the aircraft fuselage. Although extensive work has been done in the past on more slowly developing fires within an intact fuselage (commonly referred to as the "in-flight" fire), which were readily controlled by the experimentalist, all commercial transport fire fatalities during the last decade involving U.S. carriers have resulted from the post-crash fire. The hazards of post-crash aircraft fires are usually associated with the burning of large quantities of spilled fuel, but in some survivable accidents, include the involvement of cabin interior materials. Survivable accidents are those accidents wherein some crew members and passengers survive or are not immobilized by the crash impact forces. For these aircraft occupants, life or death will depend on their ability to rapidly evacuate the cabin before becoming overwhelmed by the fire which usually ensues.

Fatal commercial aircraft accidents involving fires are fairly infrequent and dissimilar to one another. It, therefore, becomes difficult to discuss a typical accident. However, one can hypothesize a realistic accident scenario where burning interior materials might affect the probability of escape. In order to be as much as possible representative of past accidents, the fire originates as a pool of burning fuel, adjacent and external to the fuselage. The fuel fire must be relatively large, perhaps on the order of 100 square feet or more, in order to be realistic. If the primary concern is with the dangers of interior materials, the fuel fire by itself must not preclude escape. Therefore, the fuselage must be relatively intact along the length adjacent to

the fuel fire to prevent direct exposure of escaping occupants. How, then, are the interior furnishings and lining materials ignited by the external fuel fire?

Based on past accidents, experimental studies and a knowledge of the design of an aircraft fuselage, it is proposed that a small opening, perhaps a crash rupture or an inadvertently opened emergency exit, provides the most significant opportunity for fire to enter the cabin. This mode of fire penetration is in contrast to that presented by burnthrough of the fuselage structure. Ignition and significant involvement of the cabin interior materials by the burnthrough mode will be much later in time than when direct fire penetration through an opening occurs. This is quite apparent for the modern wide-body jet transports (e.g., B-747, DC-10, and L-1011). The cross section of these aircraft, composed of aluminum skin and heavy structural elements, a thick blanket of thermal/acoustical insulation and a composite Nomex^R honeycomb interior panel, is an effective fire barrier. During the Continental DC-10 accident at Los Angeles International Airport in 1978, it was estimated that a large external fuel fire burned for 2 to 3 minutes (before extinguishment by crash fire rescue services) without penetration through the interior paneling. Radiative heat damage to seats adjacent to melted windows suggested that this may be an earlier mechanism for burnthrough than fire penetration through skin/insulation/honeycomb paneling. Experimental studies indicate that it is the Nomex^R honeycomb panel which is the most significant cross-sectional element preventing burnthrough. In older narrow-body jets (e.g., B-707, B-727, DC-8, DC-9, etc.) furnished with vinyl-coated aluminum sidewalls, it is believed that the occurrence of burnthrough is more immediate than in wide-body aircraft.

The test articles and models used in the studies summarized in this paper were constructed of or protected with steel sheeting and ceramic insulation. This insured repeated useage of test articles and models to allow for parametric studies and provided for a constant opening area which was more amenable to data analysis. For wide-body aircraft, it is likely that the exposure conditions and hazards through an initial opening will far exceed the increase resulting from a gradually expanding opening.

DISCUSSION

Pool Fire Impact

Particularly since the advent of the wide-body transport, the quantities of fuel potentially involved in a post-crash fire are enormous. The current upper limit would be approximately

47,000 gallons (the capacity of a Boeing 747). For pool fires above 3 feet in diameter, radiation will be relatively invariant and be approximately 14 Btu/ft²sec from some envelope containing the luminous part of the fire.

Experimental data show that radiation from large pool fires can be normalized with respect to the fire diameter. This type radiation field around a quiescent pool fire is shown in figure 1. The plot shown is found by assuming that a large pool fire can be approximated by a radiating black body sphere at 1,874°F and radius r_F . The radius r_F is taken as equivalent to the pool radius, and the radiating sphere is imagined as lying on the ground. An observer standing at some distance, r_H , from the center of the fuel pool (assumed circular) will experience a heat flux which drops off with distance according to the following relationship:

$$Q = \left(\frac{r_F}{r_H} \right)^2 \frac{1}{\sqrt{\left(\frac{r_F}{r_H} \right)^2 + 1}} (14.1) \text{ Btu/ft}^2 \text{ sec}$$

This relation explicitly shows the inverse square law for the radiation. While the relation is accurate only at distances where the observer is greater than one radius r_F from the edge of the fire (i.e., $r_H > 2r_F$), it is clear that a dimensionless distance can be defined which is the ratio of the observer distance, r_H , to the pool radius, r_F . In this manner, the radiation from all pool fires of diameter greater than 3 feet can be approximated by a single curve. The practical deduction is that as a pool fire is increased in diameter, the radiation at any fixed distance from the edge of the fire will increase from a scale effect alone.

The effect of wind on large pool fires is not entirely understood at this time. Nevertheless, the major effect of wind is to redirect the fire plume either at an angle to the vertical or entirely along the ground. This depends primarily on the Froude number, or the ratio of the bouyancy of the fire plume to the momentum of the wind. The maximum convective and radiative heat fluxes to be found with wind are close to those found in a quiescent pool fire.

Convective heat flux is more difficult to measure and of lesser importance than radiative heat flux as an insult to the fuselage exterior. However, convective heating of the fuselage skin by the fuel fire may be computed by the equation

$$Q(\text{conv}) = h(T_f - T_w)$$

where h is the convective heat transfer coefficient, T_f is the flame temperature and T_w is the skin temperature. The major problem is to determine the heat transfer coefficient. For the purpose of computing "ball park" convective heat flux levels, a heat transfer coefficient of $5 \text{ Btu/ft}^2\text{-hr-}^\circ\text{F}$ based on forced convection at gas velocities of about 20 ft/sec was estimated (reference 1). Thus, depending on the actual skin temperature, the computed convective heat flux can vary from approximately 1 to $3 \text{ Btu/ft}^2\text{-sec}$. The heat transfer coefficient depends on the gas velocity; therefore, convective heat transfer will increase as the size of the fire increases. As an illustration of the importance of gas velocity, in a past experiment, the swirling motion of a firewhirl has produced total heat flux levels as high as $18 \text{ Btu/ft}^2\text{-sec}$, indicating that the convective component for this extreme condition may have been approximately $4 \text{ Btu/ft}^2\text{-sec}$ (reference 2).

An extensive series of experiments was performed in which 1 , 2 , 3 , and 4 -foot diameter model fuselages were exposed to various size pool fires (reference 3). The radiation to the interior through a doorway was measured with calorimeters on the floor and symmetry plane, and for scaled fires corresponding to large pool fires up to 64 feet square, the doorway or opening could be treated as a radiating black body of temperature $1,874^\circ\text{F}$. Figure 2 shows a representation of the heat flux to the interior. This evaluation involved fire scenarios where the fire did not penetrate the doorway, and the analysis was later confirmed with a series of large-scale tests (reference 4).

It should be noted that wind effects can cause fire penetration, and thus, the heat flux profile of figure 2 should be considered the minimum exposure to be expected around openings and doorways exposed to a major post-crash fuel fire. Fire penetration through the doorway results in convective heat flux to the ceiling as well as greater radiation to the interior. This enhanced radiation is due both to the smaller distance between the flame and interior surfaces and to the larger flame surface that is transmitting heat within the cabin.

Interior Hazards.

Whether an interior hazard will develop from an external pool fire is greatly affected by wind, door opening configuration, and fuselage orientation. The worst case is when the fire is upwind of the fuselage and there is an opening exposed to the fire as well as openings on the downwind side of the fuselage. In this case, full-scale tests and model tests have shown a rapid development of nonsurvivable thermal conditions within

the fuselage. On the other hand, if no downwind doors are open, but instead there are additional upwind doors open but not exposed to fire, the hazard development in the cabin will be greatly retarded. These two cases are shown in figure 3. When the pool fire is downwind of the fuselage, the hazard development within the cabin will be primarily from radiation in a manner similar to the pattern described in figure 2.

In the case of no wind, heat and smoke will enter the cabin from any openings exposed to fire, but the rate of hazard development can be decreased if additional doors are opened. Because this zero wind scenario represents an intermediate case (much less severe than that occurring with convective heat moving from the fire through the cabin and out a downwind door), it has been chosen for the full-scale work with the C-133.

Heating of ceiling materials in the presence of wind near an opening adjacent to a fire will depend greatly on the amount of flame penetration. Figure 4 compares the ceiling heat flux levels for those full-scale test conditions illustrated in figure 3 in terms of cabin air temperatures. With minimal flame penetration, the ceiling heat flux ranged usually from 1 to 2 Btu/ft²-sec; however, with maximum flame penetration, the ceiling heat flux at some intervals reached 10 Btu/ft²-sec. However, in the latter case, the cabin thermal environment rapidly became nonsurvivable, emphasizing the importance of establishing heating conditions for materials under those circumstances when cabin hazards arising from the fuel fire are survivable.

Extensive probing of the cabin air environment for temperature, smoke, and gas concentration levels was performed in the C-133 wide-body test article. An analysis of these measurements is contained in reference 5. The only source of combustible material in the tests conducted to date has been the burning fuel. On the basis of measurements taken at a height of 5 feet, 6 inches, and at a location 30 feet away from the fire, it was concluded that both temperature and smoke were greater deterrents to survivability than was carbon monoxide. At this measurement location, the concentration of carbon monoxide never reached 100 ppm while under severe wind conditions, temperatures surpassed human survival limits and smoke totally obscured visibility.

The most pronounced characteristic of the C-133 cabin air environment was the significant stratification of temperature, smoke, and gases. Figure 5 shows the temperature profile at various test times under wind conditions that forced the fire

into the fuselage. The hottest temperatures were clearly concentrated in a 2-foot layer at the ceiling. The major implications of this type of profile are twofold. First, an individual who remained standing could not survive the heat while an individual who was crouched over or crawling could clearly survive. Secondly, it is apparent that materials near the cabin ceiling will be exposed to much higher convective heating rates than materials located near the floor. Figure 6 shows the smoke profile at a station near the exhaust door for the same test. During the initial part of the test, the smoke density increased monotonically from the floor to the ceiling. However, for an interval of about 1 minute, the smoke density at 3 feet, 6 inches, was higher than at 5 feet, 6 inches. This crossover in data was caused by the complex fire dynamics at the exhaust door. Apparently, a portion of the smoke exhausting at the upper portion of the door was recirculated into the cabin by entrainment with the cooler air drawn into the cabin at the lower portion of the door. At the door opening adjacent to the fire, another interesting fire phenomenon has been observed in both full-scale and model tests. In this situation, some combustion products entering the cabin can be recirculated back into the fire by entrainment with cooler lower cabin air drawn into the fire. The complex fire dynamics existing at the fire and exhaust door openings underline the difficult task confronted by theoretical cabin fire modelers.

Current Work.

Current model and full-scale tests involve studying the performance of interior materials and determining their contribution to cabin hazards. For example, one-quarter scale model tests have been conducted recently to examine the effect of burning cabin materials on heat stratification and the burnthrough resistance of in-service and advance window materials. Studies are underway in the C-133 test article to examine fire development in a 20-foot section completely furnished and lined with in-service wide-body materials (so-called "self-extinguishing" types) and to measure the cabin hazards produced by the burning interior materials. Future studies include determining the reduction in cabin hazards resulting from the usage of highly advanced materials.

CONCLUSIONS.

The broad spectrum of results derived from the external pool fire tests support conclusions which have a definite impact on future full-scale tests, model tests, and bench-scale flammability, smoke, and toxicity tests. The conclusions are as follows:

1. The external fuselage will sustain heat fluxes of at least $14 \text{ Btu/ft}^2\text{-sec}$ in any major post-crash fuel fire.

2. From radiation alone, cabin materials in the vicinity of fuselage openings can be exposed to the continuous range of 0 to $14 \text{ Btu/ft}^2\text{-sec}$.

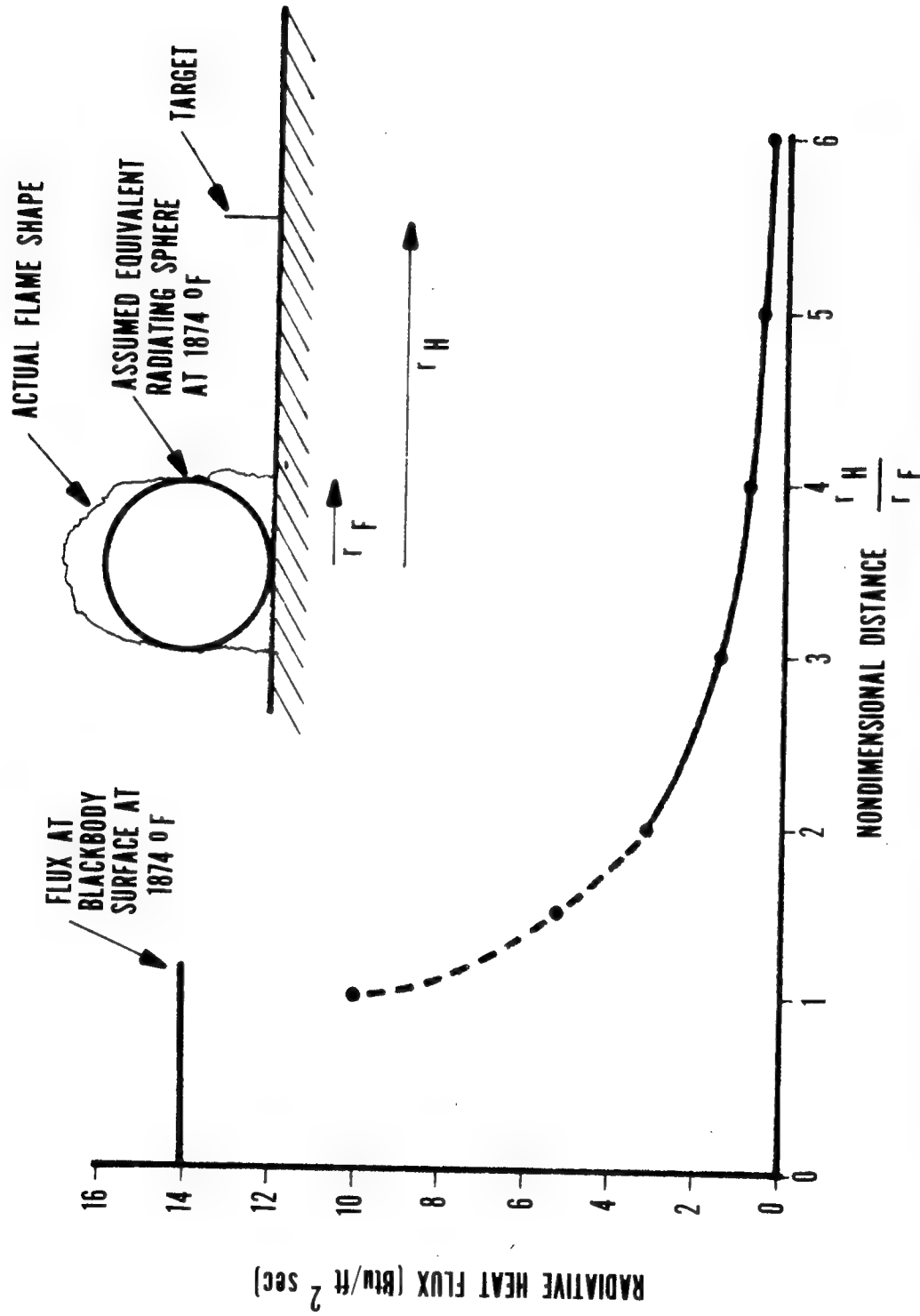
3. The interior convective heat transfer during the first 90 seconds of a fire will be dominated by wind conditions on fuselage openings. One extreme will result in no fire penetration at all. The other will result in convective heat flux through openings to such an extent that the cabin will quickly become nonsurvivable.

4. As in studies of the "in-flight" fire, temperature and smoke are characterized by marked stratification. This has a direct bearing both on evacuation (emergency exit lighting location, for instance) and on the relevance of laboratory-scale tests exposures (ceiling materials are subjected to higher convective heat fluxes than are carpets, for instance).

Nevertheless, of all the above conclusions, the one of most significance to current programs is the magnitude of the radiative flux to the interior. Since there is no a priori method of predicting where the fuselage will break or doors will be opened in a crash, future improved flammability standards should incorporate large heat fluxes in their exposure conditions.

REFERENCES.

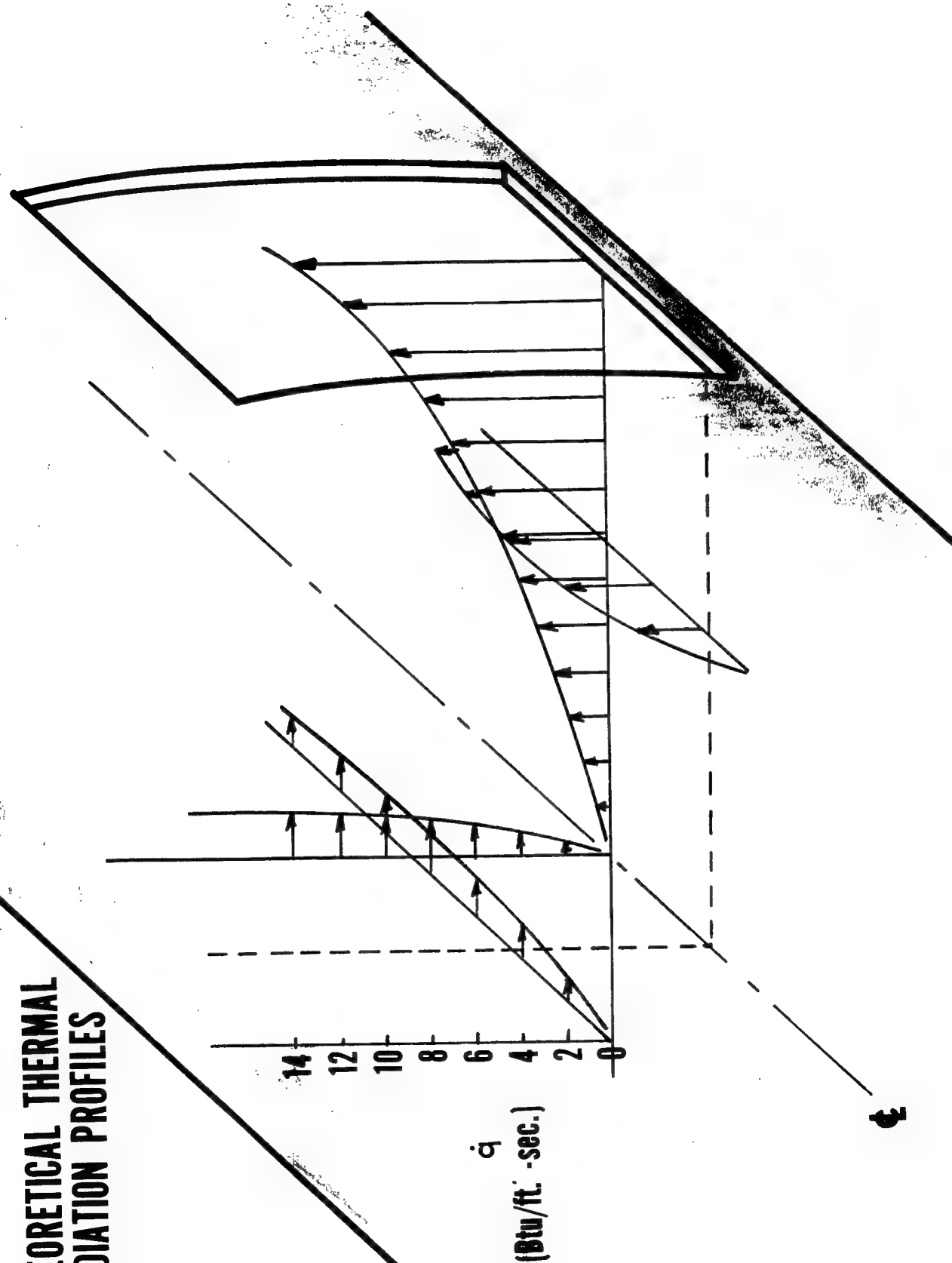
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POOL FIRE HEAT FLUX VERSUS NONDIMENSIONAL DISTANCE

FIG. 2

THEORETICAL THERMAL RADIATION PROFILES



DC7 CEILING TEMPERATURE HISTORIES

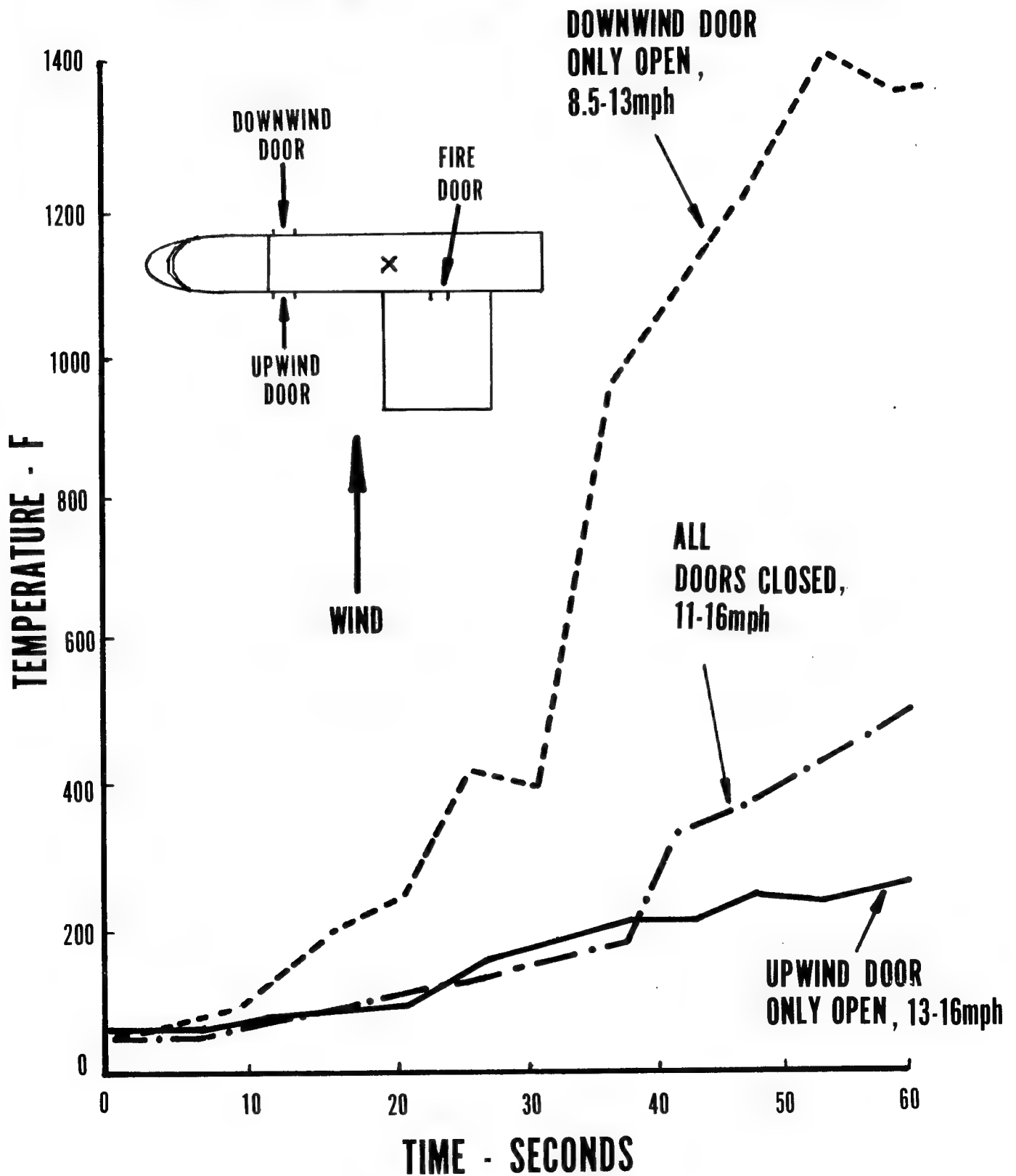
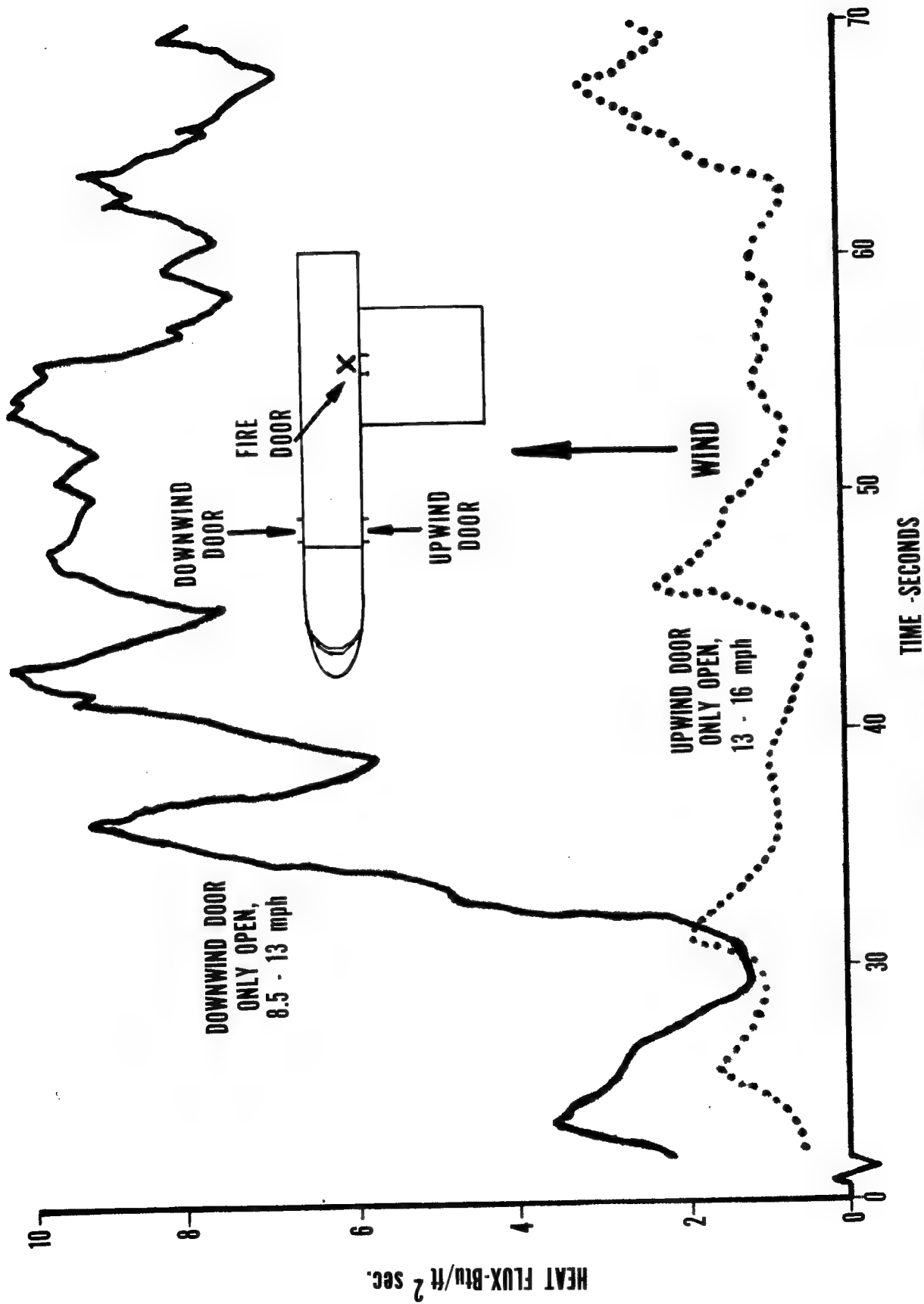


FIG. 3



DC-7 CEILING HEAT FLUX HISTORIES

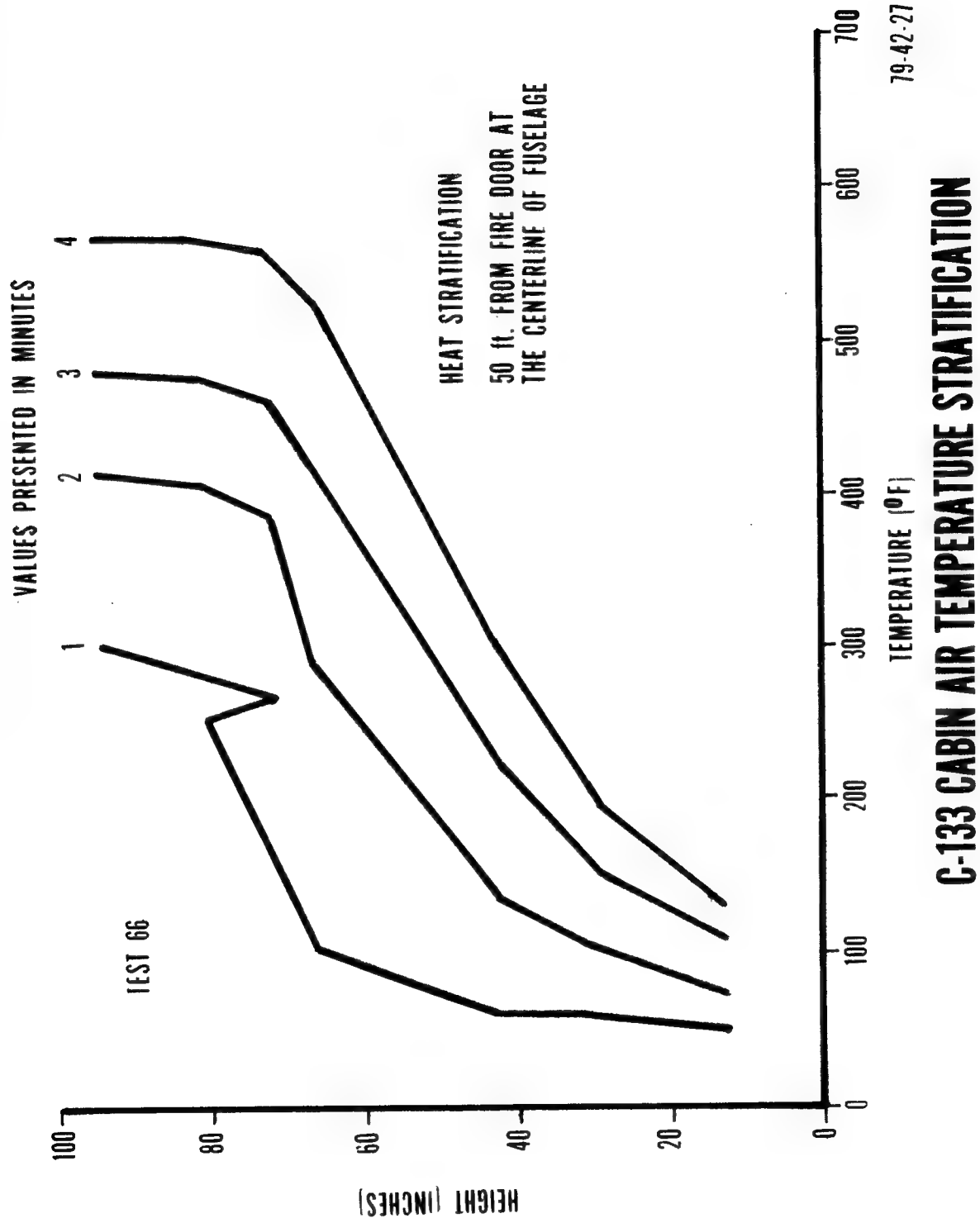


FIG. 5

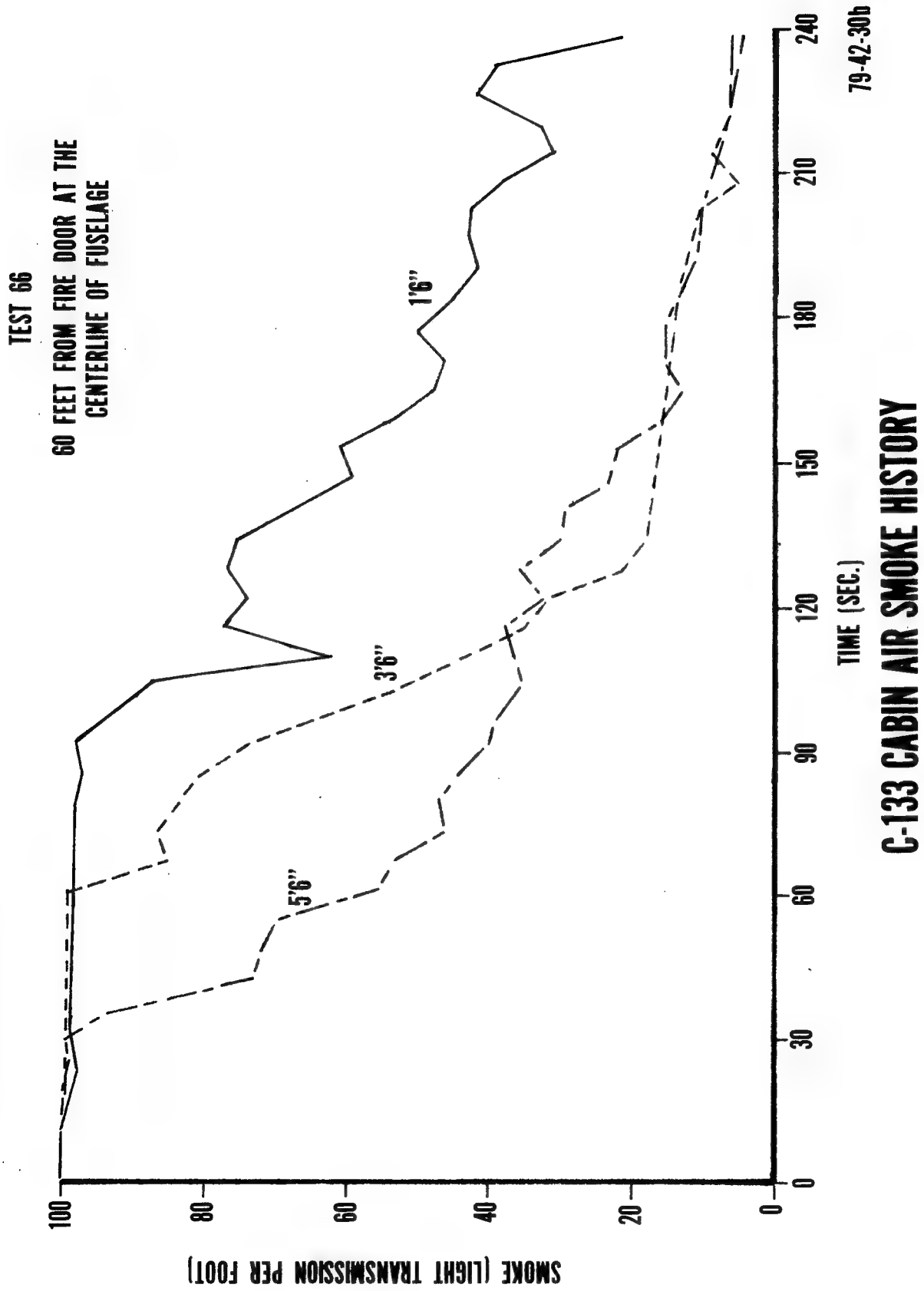


FIG. 6

COMPUTERIZED MATERIALS DATA BANK

I. Litant

Transportation Systems Center

U.S. Dept. of Transportation

INTRODUCTION

A Computerized Materials Data Bank was developed by the DOT/Transportation Systems Center as part of its support to UMTA in a program directed at improving transit system safety and providing information to the transit industry. In part, that program is concerned with the fire characteristics of non-metallic materials used in transit systems.

In a fire such as might occur on a public passenger vehicle or in any part of a transit facility, the combustibles must be controlled so that ideally: (1) they will be very difficult to ignite; and if they do ignite, flame propagation will be slow, (2) smoldering or burning objects will not produce enough smoke to obscure the means of egress in the time required to evacuate the area, and (3) gaseous degradation products from the heated or burning materials will not be lethal in the quantities produced.

The need for such a data bank became apparent when a companion project was instituted to provide the transit systems with voluntary guideline specifications for the flammability and smoke emission characteristics of the combustible materials used in the construction of new vehicles and in the refurbishment of older vehicles.

Materials of interest are included in the data bank whether or not they meet the current voluntary guideline specifications.

There is a very large body of data on the flammability characteristics of materials of interest to transit systems; however, the testing methods used to obtain this data vary considerably. For example, there are many standard methods for measuring ignition temperatures, flame propagation, heat release, and other parameters related to burning materials. Similarly, there are many methods for measuring the smoke emitted by materials undergoing thermal degradation.

Although relatively few of the standard test procedures are relevant to the requirements of the UMTA program, the body of information has become very large and unwieldy. A means was therefore sought to store the data in such a manner that pertinent information could be made easily available upon request. Usually, requests for information on materials and their properties require a cumbersome search of files, journal articles and manufacturers' literature. Comparison of flammability data on several materials is an even more arduous task. Therefore, a computerized information storage and retrieval system was devised to accommodate such data queries.

The data bank is operated on TSC's DEC System computer and utilizes 1022-software, the resident data-base management system. A contract was awarded to the Boeing Commercial Airplane Co. to manipulate this information storage system into one that would be useful for the storage and retrieval of the large number of categories and subcategories of materials of interest.

DATA BANK ORGANIZATION AND OPERATION

The data bank is structured in two informational categories: (1) non-metallic materials and (2) fire extinguishment data. Our present concern is with the materials data base, and we will address only that portion in this paper.

The design of the data bank allows for storage and rapid retrieval of the desired data. The primary consideration that fixed the structure of the data bank was the requirement that it should house and allow ready access to materials properties needed for designing a variety of items used in transit systems (seats, wall and ceiling panels, flooring, wires and cable, etc.).

Three separate types of information are stored for each material. These are:

- o Materials identifiers (manufacturer's designation, materials type, materials use, etc.).
- o Identification of data sources (report number, etc.).
- o Materials data (test methods and results).

This information provides for a comprehensive materials data base for use by system designers, planners, and regulatory officials concerned with operational safety.

Materials Identifiers

The materials are identified by manufacturer, commercial designation, materials utilization, materials type (form), and materials composition.

The manufacturer and associated commercial designation are entered in their entirety or suitably abbreviated to fit the terminal's space allocation.

Materials utilization (component type, i.e. flooring, wall), and materials composition are all entered in coded form. The use of codes permits conservation of computer storage and simplification of input. A large number of codes have been provided for these items. New codes can be entered by the programmer to cover those materials aspects not previously included. The component-type categories consist of the following:

- Adhesives
- Acoustical Insulation
- Ceiling Panels
- Carpets
- Draperies/Curtains
- Elastomers
- Electrical Insulation
- Flooring
- Lighting Diffusers
- Liners
- Plastic Windows
- Seat Cushions
- Seat Frames
- Thermal Insulation
- Upholstery
- Wall Panels
- Other Components

An example of the procedure utilized in interpreting the materials identifiers' codes is shown below:

| <u>MANUFACTURERS DESIGNATION</u> | <u>MANUFACTURER</u> | <u>COMPONENT USE</u> | <u>MATERIAL CODE</u> |
|--------------------------------------|---------------------|--------------------------|--------------------------|
| HETRON 325 FS | ASHLAND CHEMICALS | WP | DUCBGD |

This means that the material, HETRON 325 FS, is a WP (Wall Panel material) manufactured by Ashland Chemicals. It is a sheet plastic (DU), made of polyester (CB) and is reinforced with fiber glass (GD).

MATERIALS DATA

The data source is entered in the form of a report number, and the identification of the performing facility (in code). Several facilities are identified, and others may be added. Currently, the data has been generated from two principal sources: the FAA/NAFEC Fire Safety Branch and the materials testing area of the Boeing Company Technology Group. Data from tests performed by commercial testing laboratories, or by the material vendor, are so identified.

Data from the NASA Non-Metallic Materials Design Guidelines Test Data Handbook is not included for two reasons:

- 1) The NASA test procedures are standard only to NASA, and
- 2) The test environments are either at other than atmospheric pressure, or at other than normal oxygen/nitrogen ratio.

The data bank has been designed so that a broad variety of materials data acquired by different test methods can be stored. Test types include flame spread indices, smoke emission, toxic gas evolution; chemical, physical, mechanical and electrical properties; and maintainability and durability. Cost has not been included because of the difficulty in updating.

Individual records that are stored refer to test methods by code. In any given test, the results that are obtained normally consist of more than one measurement. These may consist of test parameters or test results. The present design of the data bank makes it possible to store up to twelve "measurements" for each type of test. This provides the system with its unique versatility, since each of the twelve measurements provides a piece of data, depending on the particular

test method, such as: sample thickness, number of samples used, heat flux, Ds (Flaming) (1.5 min.), Ds (Flaming) (4 min.), critical radiant heat flux, etc.

Individual materials may be retrieved by the use of an assigned identification number. For comparison purposes, groups of materials may be retrieved based on a variety of categories, for example, by specific manufacturer, chemical composition, test procedure, data source, or use category. Moreover, the items may be retrieved by specific upper and lower values of test data in ascending or descending order.

In summary, the following items are included under the following identifiers:

Manufacturer's Designation

Manufacturer

Component Use

Material Type and Composition

Flame Spread Index

Smoke Evolution

Toxic Gas Evolution

Physical, Mechanical and Electrical Properties

Chemical Properties

Maintainability and Durability

Test results are listed by the particular test procedure that was used as well as the testing organization and the date of the test. The data are available in the English system or in the equivalent metric system.

Further examples will be presented later in this paper.

Data Validity

Since the value of any data base is no better than the validity of the data stored therein, it is of utmost importance that any data entered is from a source that is judged for its competency. Furthermore, each data item is first scanned to determine whether it is consistent with its composition. Although this requires judgment on the part of the scanner, it is expected that the latter has sufficient expertise to note discrepancies and will require further testing

of the particular data. A contract is maintained with FAA/NAFEC to run validation tests of materials data of particular interest to UMTA and of promise as a material with notably good fire-resistant characteristics. Such data is also forwarded to the manufacturer.

It must be understood that a certain spread in data can be expected when a given material is tested in different laboratories. Greater than normal data spreads signal that the discrepancy must be resolved.

Periodically, data on materials from each manufacturer will be retrieved and sent to that manufacturer for comment. Over a period of time, manufacturers may make changes in formulations or even drop certain products. It is usually their practice to assign a new designation to the new formulation, but occasionally this is not done. Even small changes in formulation can produce changes in flammability, smoke and toxic gas emission as well as in other characteristics.

Data Bank Operation

The data bank is operated on the TSC's DEC System 10 computer and utilizes the resident System 1022 software. The computer is accessed from teletype-compatible terminals currently available at TSC (such as the Hazeltine 2000 or the CDI 1030, both of which have hard copy printed output capabilities). The data base is protected from unauthorized usage by System 1022 software passwords and is therefore at present accessible only from TSC and another authorized source.

Three logical groups of data manipulation capabilities are provided in the data bank design:

- o Selection of Data.
- o Display and Printout of Data.
- o Maintenance of Data.

Data Retrieval

The Data Bank is accessible on TSC computing equipment in a conversational mode by personnel with a minimal background in computers.

An inquirer seeking information from the data base is requested by the computer to respond to a series of questions, which the computer uses to identify and recall the appropriate data. The data are then displayed at the terminal. Data from several materials or an entire category of materials can be arranged using simple and appropriate conversational commands to the computer, to rank materials in either increasing or decreasing order of merit. Such ranking can be done on the basis of any of several criteria (each generally the result of a test type), so that design trade-offs can be effected. With this ability it is then possible to select all the materials within a particular component category and arrange these materials on the basis of certain fire test result priorities. Figure 1 shows an example where several carpets were tested and ranked in the data bank printout according to their critical radiant heat flux (meas. #2).

Display and Printout of Data

After the desired set of data has been identified and selected, the values of the data can be displayed immediately at the terminal. One feature which should be emphasized is the user's ability to specify the order in which the data is displayed. This data may be sorted and displayed in several forms depending on the desired data use. A printed copy of this data may then be obtained at the terminal printer or through the TSC computer center.

A high volume display capability has been provided so that a high speed printer can be used when the entire data base or a large selected set is to be displayed.

Figures 2 and 3 represent a sample of the type of printout available for a specific material on which several tests have been performed. Displayed in the left column of both figures is the material identification number (MAT ID, BWP 016). Each material in the data base has its own unique identification number. The remaining information on the figures is self-explanatory.

Maintenance of Data

Maintenance involves deleting, changing, or adding new information to the data base. Maintenance operations are protected by special passwords. These operations allow the programmer to make alterations to any record in the data base. This may involve changing any data item for any record in the data base, adding records, and deleting records.

| MAT ID | MANUFACTURER'S DESIGNATION | MANUFACTURER | TEST METHOD | MEAS. # 2 |
|--------|----------------------------------|---------------------------------------|-------------|-----------|
| TCT003 | CARPET, FIBERGLASS/WOOL | CAROLINA NARROW FABRIC | F22 | 1.2000 |
| TCT002 | CARPET, FIBERGLASS/WOOL | CAROLINA NARROW FABRIC | F22 | 1.2000 |
| TCT001 | CARPET, FIBERGLASS/NO-MEX | CAROLINA NARROW FABRICS | F22 | 1.1000 |
| TCT004 | CARPET, FIBERGLASS/WOOL | CAROLINA NARROW FABRIC | F22 | 1.1000 |
| TCT008 | ANTRON III, L8826-9, LEVEL LOOP | LEES CARPET (no underpad) | F22 | 0.9700 |
| TCT015 | FRP-251 CARPET | BURLINGTON IND. (LEES) | F22 | 0.7500 |
| TCT016 | RELIABILITY 273, CARPET | BURLINGTON IND. (LEES) | F22 | 0.7200 |
| TCT014 | THRESHOLD 274 CARPET | BURLINGTON IND. (LEES) | F22 | 0.6700 |
| TCT013 | FRP-200 CARPET | BURLINGTON IND. (LEES) | F22 | 0.6000 |
| TCT010 | SIDEMALL, LOOP, J-2507.2 | COMMERCIAL CARPET CO. (no underpad) | F22 | 0.5400 |
| TCT006 | PLAZA SQUARES, L8089, VELVET | LEES CARPET | F22 | 0.2700 |
| TCT009 | ANTRON III, L 8826-9, LEVEL LOOP | LEES CARPET (with underpad) | F22 | 0.2700 |
| TCT007 | PLAZA SQUARES, L8089-11, VELVET | LEES CARPET | F22 | 0.1300 |
| TCT011 | SIDEMALL, LOOP, J-2507.2 | COMMERCIAL CARPET CO. (with underpad) | F22 | 0.1000 |

FIGURE 1. CARPET MATERIAL RANKED ACCORDING TO CRITICAL RADIANT PANEL HEAT FLUX

MAT ID
BWP016

MANUFACTURER'S DESIGNATION:
SHEET-MOLDING COMPOUND 9300-30

MANUFACTURER

HAVEG

| FIELD | CODE | INTERPRETATION |
|------------------------|------|-------------------|
| COMPONENT USE CODE | VV | NOT SPECIFIC |
| MATERIAL TYPE CODE | AZ | COMPOUND, HOLDING |
| MATERIAL COMPOSITION 1 | CB | POLYESTER, N.O.C. |
| MATERIAL COMPOSITION 2 | FV | FIBERGLASS FABRIC |

| MAT ID | TEST METH CODE | TEST FAC CODE | DATA SOURCE CODE | TEST DATE | INTEGER OF IDENTIFICATION |
|--------|----------------|---------------|------------------|-----------|---------------------------|
| BWP016 | FJ0 | B0 | | 7/12/1978 | 1517 |

| FEDERAL AIR REGULATION 25, VERTICAL TESTS | TEST PROCEDURE | TEST REPORT NUMBER | MISCELLANEOUS NOTES |
|---|----------------|--------------------|---------------------|
| | | BMT 78-00368 | |

| TEST RESULT | UNIT OF MEASURE | IGNITION TIME | TEST RESULT NAME |
|-------------|-----------------|---|------------------|
| 60.0000 | SECONDS | SELF-EXTINGUISHING TIME, ISOTRGPIC/WARP | |
| 1.7000 | SECONDS | BURNED LENGTH, ISOTROPIC/WARP | |
| 1.8000 | INCHES | DRIP EXTINGUISHING TIME, ISOTRDPIC/WARP | |
| 0.0000 | SECONDS | SELF EXTINGUISHING TIME, FILL | |
| 1.9000 | SECONDS | BURNED LENGTH, FILL | |
| 1.7000 | INCHES | DRIP EXTINGUISHING TIME, FILL | |
| 0.0000 | SECONDS | | |

97

| MAT ID | TEST METH CODE | TEST FAC CODE | DATA SOURCE CODE | TEST DATE | INTEGER OF IDENTIFICATION |
|--------|----------------|---------------|------------------|-----------|---------------------------|
| BWP016 | F14 | B0 | | 7/21/1978 | 1518 |

| ASTM E 162: MAIL SURFACE FLAMM USING RADIANT ENERGY | TEST PROCEDURE | TEST REPORT NUMBER | MISCELLANEOUS NOTES |
|---|----------------|--------------------|---------------------|
| | | BMT 78-00368 | |

| TEST RESULT | UNIT OF MEASURE | MATERIAL THICKNESS | TEST RESULT NAME |
|-------------|-----------------|---|------------------|
| 0.0750 | INCHES | NUMBER OF SPECIMENS | |
| 4.0000 | | FLAME SPREAD FACTOR FS | |
| 2.8000 | | STANDARD DEVIATION OF FLAME SPREAD FACTOR FS | |
| 1.4000 | | HEAT EVOLUTION FACTOR Q | |
| 4.7000 | | STANDARD DEVIATION OF HEAT EVOLUTION FACTOR Q | |
| 0.2000 | | FLAME SPREAD INDEX IS | |
| 13.2000 | | STANDARD DEVIATION OF FLAME SPREAD INDEX IS | |
| 6.7000 | | | |

Figure 2.

| | | | | | | |
|--|-----------------------|---------------------|-------------------------|---|-----------------------------------|---------------------|
| MAT ID BWP016 | TEST METH CODE S11 | TEST FAC CODE 80 | DATA SOURCE CODE | TEST DATE 8/1/1978 | INTEGER OF IDENTIFICATION 1519 | MISCELLANEOUS NOTES |
| TEST PROCEDURE | | | | | | |
| NATIONAL BUREAU OF STANDARDS SMOKE DENSITY CHAMBER | | | | | | |
| | | | UNIT OF MEASURE INCH | TEST RESULT NAME | | |
| TEST RESULT 0.0750 | | | MATERIAL THICKNESS | THERMAL FLUX OF HEATER | | |
| 2.5000 | | | WATT/SQCM | SPECIFIC OPTICAL DENSITY AT 1.5 MINUTE, FLAMING | | |
| 13.1000 | | | | STD DEV DS AT 1.5 MINUTE, FLAMING | | |
| 5.1000 | | | | SPECIFIC OPTICAL DENSITY AT 4.0 MINUTE, FLAMING | | |
| 150.0000 | | | | STD DEV DS AT 4.0 MINUTE, FLAMING | | |
| 21.3000 | | | | MAXIMUM SPECIFIC OPTICAL DENSITY, FLAMING | | |
| 276.2000 | | | | STD DEV DMAX, FLAMING | | |
| 27.1000 | | | MIN | TIME TO MAXIMUM SPECIFIC OPTICAL DENSITY, FLAMING | | |
| 10.8000 | | | MIN | STD DEV TIME TO DMAX, FLAMING | | |
| -1.0000 | | | | | | |

| | | | | | | |
|---|-----------------------|---------------------|----------------------------------|--------------------------------|-----------------------------------|---------------------|
| MAT ID BWP016 | TEST METH CODE T03 | TEST FAC CODE 80 | DATA SOURCE CODE | TEST DATE 5/25/1978 | INTEGER OF IDENTIFICATION 1520 | MISCELLANEOUS NOTES |
| TEST PROCEDURE | | | | | | |
| MUS SMOKE CHAMBER: CONCENTRATION OF EVOLVED GASES | | | | | | |
| | | | UNIT OF MEASURE PARTS/MILLION | TEST RESULT NAME | | |
| TEST RESULT 135.0000 | | | | CARBON MONOXIDE, FLAMING | | |
| 0.0000 | | | | OXIDES OF NITROGEN, FLAMING | | |
| 0.0000 | | | | HYDROGEN FLUORIDE, FLAMING | | |
| 17.0000 | | | | HYDROGEN CHLORIDE, FLAMING | | |
| 2.0000 | | | | HYDROGEN CYANIDE, FLAMING | | |
| 0.0000 | | | | SULFUR DIOXIDE, FLAMING | | |
| 0.0000 | | | | CARBON MONOXIDE, SMOLDERING | | |
| 0.0000 | | | | OXIDES OF NITROGEN, SMOLDERING | | |
| 0.0000 | | | | HYDROGEN FLUORIDE, SMOLDERING | | |
| 0.0000 | | | | HYDROGEN CHLORIDE, SMOLDERING | | |
| 0.0000 | | | | HYDROGEN CYANIDE, SMOLDERING | | |
| 0.0000 | | | | SULFUR DIOXIDE, SMOLDERING | | |

Figure 3.

Capability is also provided to add, change, or delete any of the test methods or materials identification codes.

Operational Alternatives

The majority of materials data contained in the data base concerns information on materials common to all transportation modes and is not limited to transit systems. As such, the data bank is of value to all agencies of the Department of Transportation. Furthermore, other agencies and sectors of industry would find the data bank useful.

At present, the data bank is accessible only at TSC and to the contractor presently involved in updating it. To obtain data on a material, an organization must contact the TSC data bank operator and request the desired data. This arrangement, when combined with the low visibility the data bank now has, may tend to limit its usefulness to a small portion of the technical community. The following options are now under consideration:

1. Continue the operation as currently being performed.
2. Access from outside terminals on "Read Only" basis.
3. Requested data to be provided by TSC Computer Services Division on a pay-as-you-go basis.
4. Cost-sharing with other DOT Agencies.
5. Combine this data bank with another system.
6. Publish all data periodically.

In conclusion, TSC has developed and maintains a materials data base designed for storage and rapid retrieval of data in a wide variety of materials categories containing a large number of materials. Although the data base is primarily directed toward flammability characteristics, wherever possible, mechanical, physical and chemical properties are included.

The data is retrievable in any of the categories as well as by each of the test data items.

The data bank is already being used by designers of transit systems, and should eventually be of value outside of the ground mass transportation area.

FIRE RESEARCH INVOLVING RADIOACTIVE SPENT FUEL CASKS

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ABSTRACT: Fire problems involving radioactive spent fuel casks are described. Past and ongoing research to solve these problems are discussed.

Background

The safety of commercial nuclear power production is very much of concern to the public. One particular aspect of this problem is the transportation of radioactive spent fuel rods from nuclear power plants to reprocessing plants or storage sites. Because of the unresolved issues concerning the reprocessing/storage of spent fuel, there have been few shipments of spent fuel from commercial power plants. However, many of the existing power plants are reaching their in-plant storage capacities. Therefore, it is anticipated that in the 1980s there will be a dramatic increase in spent fuel shipments, even without any increase in the number of nuclear power plants. Because of economic and safety considerations, it is expected that most of these shipments will be by rail (1).

One situation that might occur in the rail transportation of spent fuel is the subjection of the cask to a fire. This could occur because of a derailment, head puncture, or other accident involving a nearby railroad car carrying a flammable commodity. Department of Transportation (DOT) regulations (2) specify that when a cask is subjected "to a radiation environment of 1475 F for 30 minutes with an emissivity coefficient of 0.9, assuming the surfaces of the package have an absorption coefficient of 0.8", the radiation dose rates and leakage of radioactive material must be within certain limits. Because of the large costs involved in the manufacture of spent fuel casks, it is not feasible to subject every spent fuel cask design to fires and other required destructive tests. Therefore, the regulations state that "it is not necessary to actually conduct the tests prescribed in this section if it can be clearly shown, through engineering evaluation or comparative data, that the material or item would be capable of performing satisfactorily under the prescribed test conditions."

There are two uncertainties involved in these regulations. First, is the 30 minute, 1475 F fire requirement adequate? There have been a number of railroad fires in which the fire duration and/or intensity has exceeded that requirement. Second, what analysis and/or small scale testing is necessary to demonstrate that the performance of the cask is adequate under actual fire conditions? To resolve these uncertainties the Departments of Energy and of Transportation have sponsored fire research programs.

Research Activities

In recent years the Department of Energy (DOE), and its predecessor agencies, have sponsored work at Sandia Laboratories for the development of analytical models capable of predicting the response of spent fuel casks to pool fires. In addition, DOE sponsored a full scale pool fire test in January, 1978 of an obsolete cask. That test was intended to validate the previous analytical work. Unfortunately, the full scale results were ambiguous, apparently due to a defect in the cask. Moreover, it was difficult to extrapolate the obsolete cask test results to predict what would have occurred to a modern cask.

In September, 1978 DOE and DOT embarked on an expanded fire research program. The following activities are planned:

1. A refinement of the analytical modeling. It is planned to consider the possibility of torch fires in the analysis. Also, a broader spectrum of cask designs will be considered.
2. The fabrication and testing of small scale model casks. In this activity representative cask designs will be selected for testing and small scale models of these designs will be fabricated. These models will then be subjected to the torch and pool fire tests specified by DOT regulations (3) for certain tank cars.
3. The modification and testing of a full scale obsolete cask. In this activity an obsolete cask will be modified to resemble, as much as possible, a modern cask. This cask will then be subjected to the torch and pool fire test specified by DOT regulations (3) for certain tank cars.

It is anticipated that the above program will be completed in FY 1982. As of January, 1980 the first activity is nearly complete. However, it is anticipated that revisions to the analytical modelling may be necessary as test results are obtained from the other activities. Work on the other two activities is in progress.

Summary

The vulnerability of radioactive spent fuel casks to fires is unknown at present. DOE and DOT have an ongoing research program to quantify that vulnerability.

References

1. "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes" (NUREG-0170), U.S. Nuclear Regulatory Commission, December 1977
2. Code of Federal Regulations, Title 49, Paragraph 173.398
3. Code of Federal Regulations, Title 49, Part 179, Subpart C

USE OF FIRE DEPARTMENT DATA IN EVALUATION
APPLICATION TO FMVSS 301

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ABSTRACT

Federal Motor Vehicle Safety Standard #301 was promulgated to foster vehicle designs which were less susceptible to leaking fuel and catching fire following a crash. After several years' experience with the standard, an effort was made to estimate the change in post-crash fire rates related to the standard. Most sets of accident data do not contain information about the occurrence of fire, so data from fire departments were sought to identify car fires. The car fires identified in fire department data were then related to exposure (number of crashes or number of registered vehicles) for each group of model years corresponding to the versions of FMVSS 301 to estimate the effect of the standard.

Fires following a crash were found to be a very small fraction of car fires. In addition, it was very difficult to determine which car fires in statewide fire department data resulted from crashes. These facts limited the utility of fire department data in the direct evaluation of FMVSS 301. However, fire department data such as those collected by the National Fire Incident Reporting System (NFIRS) can be quite useful in developing other data about car fires. An example is the relation of the frequency of arson to the age and model of the car. One result found is that the newer cars--built in compliance with progressively more stringent versions of FMVSS 301--have considerably lower fire rates than do older cars. A strong trend toward increasing fire rates with increasing age of the car was found. Since crash fires are such a small percentage of all car fires, it was difficult to relate this trend directly to the standard. However, combinations of several data sources estimated a reduction of nearly 16 percent in the occurrence of crash fires for models built since the original version of FMVSS 301, and an additional reduction of nearly 14 percent in crash fires was observed coincident with the current version of FMVSS 301.

INTRODUCTION

A fire following the crash of a motor vehicle is a spectacular and potentially lethal event. Such occurrences pose a very visible additional risk of injury or death to passengers. The National Highway Traffic Safety Administration (NHTSA) promulgated Federal Motor Vehicle Safety Standard 301, Fuel System Integrity, in an attempt to reduce this risk. The earliest version of this standard

took effect on January 1, 1968, and thus applied to most of the 1968 and all later models of passenger cars. Compliance with the standard was to be demonstrated by a frontal impact at 30 mph into a fixed barrier, following which the vehicle was supposed to retain its fuel system integrity, i.e., not leak fuel at a rate of more than one ounce per minute.

In 1973 the standard was amended and strengthened. After some delays, one of the additional provisions was applied to the 1976 model year vehicles; most first affected the 1977 and later model years. For the 1976 models, the additional requirement to demonstrate compliance was that the vehicle should not leak fuel following the 30 mph frontal impact when placed in any of four resting positions: on either side, top, or wheels. Additional requirements for 1977 included similar performance upon rear impacts with moving barriers at 20 mph, and with side/angle impacts with moving barriers. These later versions of the standard were also applied to light trucks and school buses as well as passenger cars. The precise details of the standard may be found in the Federal Register: 32 F.R. 2416, February 3, 1967, 38 F.R. 22397, August 20, 1973, 39 F.R. March 21, 1964, and 40 F.R. 48352, October 15, 1975.

The National Fire Incident Reporting System (NFIRS) is a centralized system for collecting data from fire departments. Each state that participates in the NFIRS collects data reported from local fire departments in its state. These state files are then assembled in Washington by the NFIRS. All of the participating states use a standard form and the 901 code manual for reporting data. The National Fire Prevention and Control Administration, later the U.S. Fire Administration, and currently a component of the Federal Emergency Management Agency, is now developing the NFIRS and extending it to more states. The level of detail in NFIRS about vehicle fires makes this source of data potentially valuable in estimating the effectiveness of changes in vehicle design brought about in connection with various versions of FMVSS #301. This paper will discuss attempts to use such data in this evaluation, and indicate other potential applications of the NFIRS data.

As part of a NHTSA-sponsored evaluation of the effects of FMVSS #301, HSRI acquired and analyzed portions of the NFIRS computerized files. NFIRS data from six states--Maryland, Michigan, Missouri, New York, Ohio, and Oregon--were used. The data were for the calendar year of 1977. Attention was restricted to these states in part because of the availability of crash information to use in conjunction with the fire department data.

USE OF NFIRS DATA

FMVSS #301 specifically aims at preventing fires that occur as a result of a traffic accident. The mechanism for prevention is to reduce or prevent the leakage of fuel and thereby to minimize the ignition of spilled gasoline. One might expect two effects:

reduction in the rate of fuel spillage, and a consequential reduction in the rate of crash fires. In either case, attention for evaluation should be directed toward cars which have been involved in traffic crashes.

It seems likely that there should be more cases of fuel spillage than fire, and thus it was hoped that counts of fuel spillage could be obtained from occasions in which a fire department was called to a crash because of this hazardous condition. However, reports in the NFIRS for a purpose other than a fire proved to be rather rare. In addition, when they did occur, they were more often cases of fuel spilled from large trucks rather than from passenger cars. As a result the NFIRS data on fuel spillage was too limited to be of use in the evaluation.

To be directly applicable to the FMVSS 301, car fires should result from a traffic crash. Unfortunately, this proved very difficult to determine in the NFIRS data. There is no reported item that specifically tells whether a traffic accident was involved. There are several variables that might indicate a crash. For example, "ignition factor" has codes 41 (fuel spilled or released accidentally) and 71 (collision, overturn, knockdown) which could be the result of a crash. On the other hand, both are also used for cases not involving a crash. Similarly, the "fixed property use" could be reported as 921 (bridge) or 961 (limited access highway), 965 (uncovered parking lot), etc. None of these variables or codes exactly identifies a car fire with a crash.

SURROGATE DEVELOPMENT

While each state is encouraged to record at least the elements on the NFIRS form, the state is free to record additional information for local use. For the State of Michigan the fire marshall's office provided us with a computer file of their expanded version of the original written reports, and we were able to refer to these during the study.

Using the Michigan data, we attempted to use a combination of reported information as a surrogate for a car fire resulting from a crash. About 100 different combinations of code values and variables were tried to find one that would best predict a crash fire, the best of these being made up of the variables shown in Table 1. To check this we reviewed many thousands of written fire incident reports to select those which clearly involved crash fires. This search resulted in 64 cases (55 certain, and 9 probables) identified as crash fires. The best surrogate (combination of variables in the Michigan computer file) identified 52 cases from the computer file. Of these, 17 were non-crashes, and five were not in the hard copies for one reason or another. The remaining 30 were definite or probable crashes. Of the 64 probable crashes in the hard copies, the computer surrogate identified 30, or a little less than one-half.

TABLE 1

Factors Making Up the Crash Surrogate From NFIRS Data

| | |
|-------------------------------|--|
| Area of Origin | Mobile (passenger area, fuel tank, etc.) |
| Equipment Involved | Vehicle or internal combustion engine |
| Form of Heat Causing Ignition | Heat From Fueled Equipment |
| Use of Material First Ignited | Fuel or Power Transfer Equipment |
| Act or Omission | Fuel Spilled or Accident |
| Fixed Property Location | Highway, Public Street, etc. |

Thus, combinations of variables reported in NFIRS did not do well at identifying passenger car fires with crashes. In addition, the data from different states varied so greatly in the proportion of car fires coded "collision, overturn, or knockdown" for example, that it seemed likely that use of the codes or the reporting was not consistent from state to state. Reported frequencies for these code values for several states are given in Table 2. As a result, even had the surrogate been a better predictor in the Michigan data, it would not generalize to other states' data.

TABLE 2

"Fuel Spilled" and "Collision or Accident" Frequencies Reported to NFIRS From Various States - 1977

| State | Fuel Spilled (41) | Collision (71) | Total |
|----------|----------------------|-------------------|-------|
| New York | 34 | 54 | 88 |
| Michigan | 354 | 425 | 779 |
| Missouri | 66 | 54 | 120 |
| Ohio | 580 | 159 | 739 |
| Oregon | 25 | 84 | 109 |
| Maryland | 9 | 15 | 24 |

As a result of the difficulty in identifying car fire with crashes, and additional problems with identifying model years of cars involved in fires (model year was missing in from 20-30 percent of

the cases), the NFIRS data were of limited use in evaluating FMVSS #301 directly. However, it is possible that improving the fuel system as called for in FMVSS #301 might have the serendipitous effect of reducing all car fires. If many car fires result from fuel leakage, then the improvement might reduce this even in the absence of a crash. In all six states, reductions in the NFIRS rate of passenger car fires per reported crash or per registered vehicle were observed with the newer model years. Figures 1 and 2 illustrate this for the data from Ohio, related to crashes, and Oregon, related to registrations. In the Figures, the solid line represents a smoothed rate estimated from a model that includes a linear term for the age of the car and step functions for the different versions of the standard.

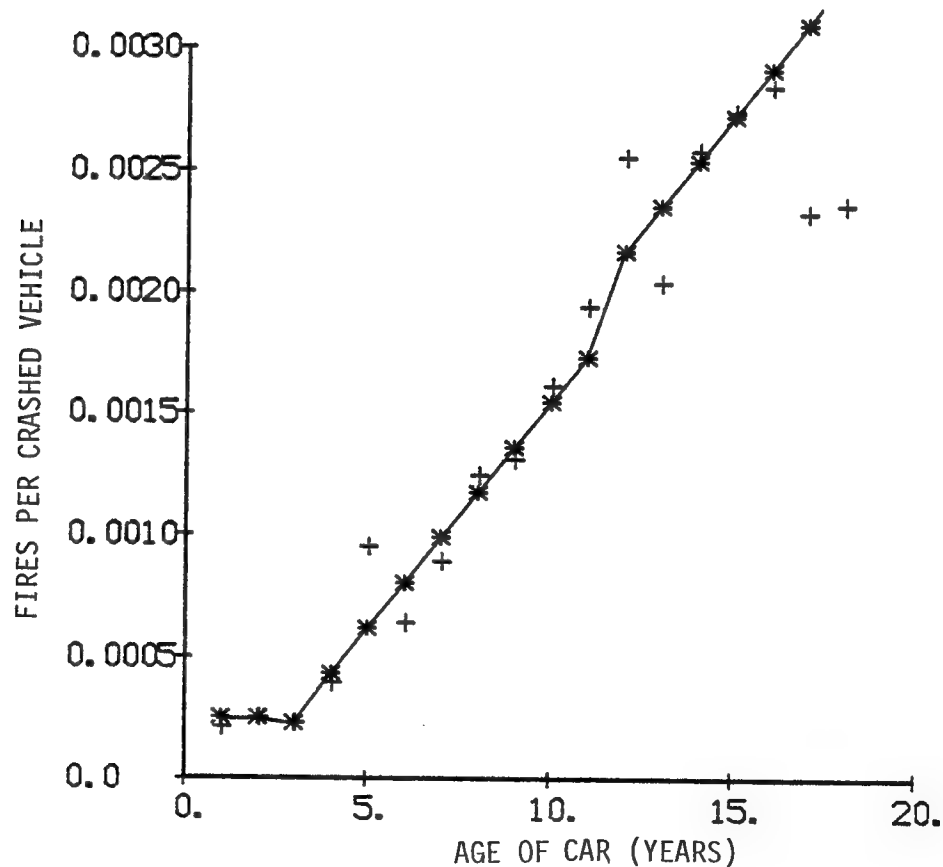


FIGURE 1
Ohio Crash Fire Ratios (1977)

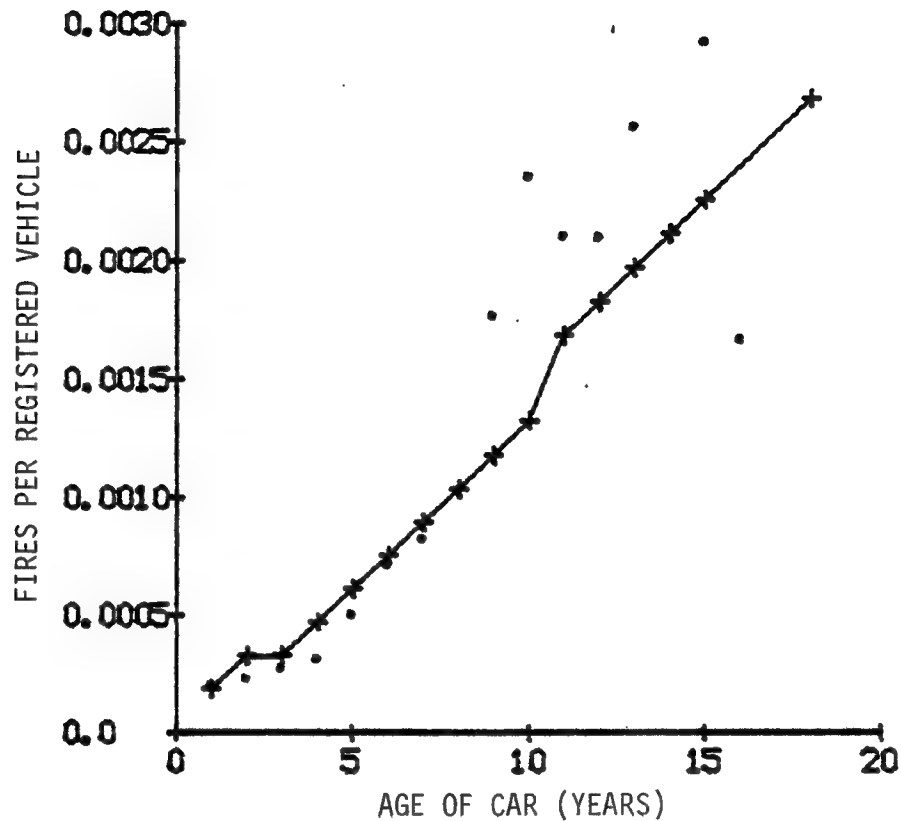


FIGURE 2
Oregon Fires Per Registered Vehicle (1977)

The data from the different states all showed similar patterns. The ratio of cars in fires to cars in crashes (as in Ohio) or of cars in fires to cars registered (as in Oregon) was consistently lower for newer models. However, this appeared to be a rather smooth increase with the age of the car, rather than a sharp or sudden increase for cars built before one of the versions of the standard. As a consequence, it may be that cars deteriorate with age, becoming more likely to catch fire as they age. If this is so, then the aging effect may be larger than the effect of designs in conjunction with versions of FMVSS #301.

Police accident data from several states include information about whether a fire occurred in a crash. These data proved more useful for estimating the effect of FMVSS #301. Two states with this information also had fire department data: New York and Michigan. In both of these states, the number of car fires reported from the police accident data differed markedly from the number reported from fire department data. In New York in 1977, 4,973 car fires were reported in the fire department data, while only 161 fires were reported in the police accident data. Either severe under-reporting occurred in the police data, or crash fires are a very small proportion of car fires--about 3.25 percent . . . or perhaps both.

In Michigan, 1,109 crash fires were reported in 1978 (the first year with fire information in the police accident data). The fire department data reported about 14,000 car fires.

Although data from fire departments were not particularly useful in estimating the effect of FMVSS #301, the reduction in car fires for newer (younger) cars is consistent with the effect estimated from the police accident data. The overall data estimated that a 15 percent reduction in crash fires occurred in connection with the first standard (1968 models) and an additional 13 percent reduction occurred with the 1967 standard. Details may be found in Flora (1980) or in Flora et al. (1979).

OTHER USES OF FIRE DEPARTMENT DATA - SOME DESCRIPTIVE STATISTICS

Although the fire department data did not prove to be directly applicable to the problem of estimating the effect of FMVSS #301, they do provide some interesting information about motor vehicle fires. Some of these are illustrated in the Michigan data from 1976-1977. In this period, fire department runs for motor vehicles constituted about 10 percent of all reported fire department calls. If the estimated effects of FMVSS #301 carry over to all car fires, then as more and more of the vehicle population consists of models that meet the standard in its current version, fewer fires would be expected. Relative to the number of cars, a reduction in calls to car fires should be observed. However, the relative scarcity of crashes as a cause of car fires may make this effect on the total fire department load negligible.

Table 3 shows how various mobile properties are distributed among reported Michigan fire runs. About 75 percent involve passenger cars. Pickup trucks, large trucks, and commercial trailers account for nearly another 12 percent.

Restricting attention to just passenger cars, 84 percent of the calls were for a fire or explosion. In Michigan, the second largest number of calls was for a hazardous condition--generally fuel spillage. Runs made for rescue, with no fire involved, totaled 3.3 percent (Table 4).

TABLE 3

MOBILE PROPERTY TYPE IN MICHIGAN FIRE DEPARTMENT RUNS
1976-1977

| Mobile Property Type | N | % |
|----------------------|--------|-------|
| Passenger Cars | 27,708 | 75.0% |
| Bus | 249 | 0.7% |
| Motor Bike | 645 | 1.7% |
| Motor Home | 359 | 1.0% |
| Camping Trailer | 157 | 0.4% |
| Commercial Trailer | 617 | 2.2% |
| Large Truck | 1,458 | 3.9% |
| Pickup Truck | 1,655 | 4.5% |
| Tank Truck | 232 | 0.6% |
| Other | 3,865 | 10.5% |

TABLE 4

PASSENGER CAR RUNS - MICHIGAN FIRE DATA - 1976-1977

| Situation Found | N | % |
|---------------------|--------|--------|
| Fire, explosion | 23,233 | 83.8% |
| Hazardous Condition | 2,218 | 8.0% |
| Rescue (no fire) | 924 | 3.3% |
| Alarm (no fire) | 773 | 2.8% |
| Other | 560 | 2.0% |
| Total | 27,708 | 100.0% |

A relatively small percentage of the fire origins are ascribed to the fuel tank--the majority being in the engine area, followed by the passenger area. As in many data sets the "other and undetermined" group is quite large, and this always leaves some doubt about the remainder of the distribution (Table 5).

The distribution of "act or omission" associated with the car is shown in Table 6. Traffic accidents would seem most likely to be coded as "accident, overturn, or knockdown," and represent less than 5% of the total. Arson and suspected arson, on the other hand, account for more than ten percent. Table 7 contains only those cases classified as arson or suspected arson, and shows the distribution

TABLE 5
PASSENGER CAR AREA OF FIRE ORIGIN

| Area | N | % |
|--------------------|--------|-------|
| Passenger Area | 5,365 | 20.2% |
| Trunk | 431 | 1.6% |
| Engine Area | 10,450 | 39.3% |
| Fuel Tank | 499 | 1.9% |
| Other/Undetermined | 9,820 | 37.0% |

TABLE 6
PASSENGER CAR FIRE RUNS - MICHIGAN 1976-1977
BY ACT OR OMISSION

| Act/Omission | N | % | Comment |
|-------------------------------|-------|-------|---|
| Arson | 1,673 | 6.0% | |
| Suspected Arson | 1,248 | 4.5% | |
| Misuse of Heat of Ignition | 2,749 | 9.9% | 1,560 discarded cigarettes, etc. |
| Misuse of Material Ignited | 1,476 | 5.3% | 709 fuel spilled |
| Part Failure | 9,841 | 35.5% | 4,050 leak/breaks, 2,674 short circuits |
| Construction of Deficiency | 412 | 1.5% | 144 "property too close" |
| Accident, Overturn, Knockdown | 1,359 | 4.9% | Should include most highway crashes |
| Natural Condition | 73 | 0.2% | High wind/Lightning |
| Other/Undetermined | 6,599 | 23.8% | |

of this factor by make of car. Cadillacs and Lincolns head the list for the relative incidence of arson in Michigan, perhaps because of their insurance value. Why Ford products are more likely to be the target of arson as compared with General Motors produces is not obvious, but the difference is significant.

Table 8 lists the ignition heat form for all passenger car fires--again with a large undetermined group. Cigarette smoking alone accounts for more cases than accidents (from the earlier list), and there were 3,983 cases of engine backfire reported. Under the explosive category (1 percent of all cases) more than half (142) were Molotov cocktails in this two-year period.

TABLE 7

CAR MAKES INVOLVED - FIRES WITH ARSON OR SUSPECTED ARSON
MICHIGAN 1976-1977

| Make | Total Number with Fire Report | Number with Arson or Suspect. Arson | % |
|-----------|----------------------------------|--|--------|
| AMC | 651 | 57 | 8.76% |
| BUICK | 1,803 | 91 | 5.05% |
| CADILLAC | 963 | 101 | 10.48% |
| CHEVROLET | 5,279 | 289 | 5.47% |
| CHRYSLER | 780 | 46 | 5.90% |
| DODGE | 1,260 | 94 | 7.46% |
| FORD | 5,493 | 418 | 7.61% |
| JEEP | 106 | 4 | 3.77% |
| LINCOLN | 385 | 54 | 14.03% |
| MERCURY | 1,273 | 74 | 5.81% |
| OLDS | 2,441 | 108 | 4.42% |
| PLYMOUTH | 1,394 | 105 | 7.53% |
| PONTIAC | 2,641 | 138 | 5.23% |
| VW | 847 | 45 | 5.31% |

TABLE 8

IGNITION HEAT FORMS - PASSENGER CARS - MICHIGAN 1976-1977

| Heat Form | N | % | Remarks |
|----------------------|-------|-------|--------------------------|
| Fuel Fired | 4,513 | 16.3% | |
| Electrical Equipment | 3,886 | 14.0% | 2,476 short circuits |
| Smoking Material | 1,609 | 5.8% | 1,323 cigarettes |
| Open Flame, Spark | 6,609 | 23.9% | 3,983 engine backfires |
| Hot Object | 1,566 | 5.7% | 457 overheated tires |
| Explosive | 273 | 1.0% | Molotov cocktails |
| Natural Source | 54 | 0.2% | 2 lightning, 10 sun |
| Another Fire | 263 | 0.9% | 97 flying embers, sparks |
| Heat (undetermined) | 8,935 | 32.2% | |

One inferential use of the Michigan data is shown in Table 7, again tabulating vehicle makes by the proportion of engine compartment fires per registered vehicle. In a statistical test of this distribution it is shown that Chevrolets have a significantly low rate, but that Cadillacs and Oldsmobiles are significantly high.

TABLE 9

CAR FIRES IN MICHIGAN BY VEHICLE MAKE AND FIRE TYPE - 1975

| Vehicle Make | Number of Registered Vehicles | Engine Compartment Fires |
|--------------|-------------------------------|--------------------------|
| AMC | 130,733 | .00306% |
| BUICK | 325,267 | .010% |
| CADILLAC | 96,781 | .0186% HIGH |
| CHEVROLET | 948,360 | .0058% LOW |
| CHRYSLER | 103,747 | .0134% |
| DODGE | 231,280 | .0043% |
| FORD | 855,018 | .0081% |
| LINCOLN | 39,436 | .0126% |
| MERCURY | 202,446 | .0119% |
| OLDS | 352,759 | .0164% HIGH |
| PLYMOUTH | 300,980 | .005% |
| PONTIAC | 380,983 | .0092% |
| VW | 128,908 | .0085% |
| TOTAL | 4,200,000 | .00871% |

The likely explanation for the high values are aging components in the fuel injection system in recent model Cadillacs, and a problem with an overheating transmission in older (pre-1970) Oldsmobiles. Both of these problems had surfaced without any direct use of the NFIRS data, but the data suggest that NFIRS may be a source for discovering such things.

CONCLUSIONS

There is little question that newer cars are less often involved in fires. The police-reported accident data show about a 25 percent reduction in crash fire frequency associated with the improvements made in connection with the Federal Motor Vehicle Standard #301 over the past ten years. The NFIRS data support this same finding, but also show a marked reduction in all kinds of fires for newer vehicles. Some of this may be attributed to design changes in the fuel systems, and some may have simply to do with age.

The NFIRS system is relatively new. It potentially has much interest for users other than those directly concerned with fire fighting and prevention. It seems clear from inspection of the present data that practices differ among the states, and this makes it difficult or impossible to produce national estimates of many of the frequencies of interest. Table 2 shows substantially different frequencies of car fires from state to state which would not be

easily explained. Many of the data sets used in this study were those produced in only the second year of operation of NFIRS within a state, and it can be hoped that further refinement of the reporting system will lead to more consistent and complete reporting.

NFIRS codes were obviously chosen for their value to fire department personnel, and they may serve that need well. Outside users, however, may have the same kinds of problems we did in identifying a group of particular interest. In our case it would have been desirable to have had a specific code which identified a traffic accident (in the same way the police report them). The hierarchical coding system in the NFIRS is a good one, and tends to reduce the volume of "missing" or "unknown" data. In spite of this there are, for some variables, substantial fractions of missing data, and one may hope that time will improve that too.

In spite of some limitations imposed by the early stage of the development of the NFIRS, the data are useful in a variety of situations in addition to those of the fire departments themselves. With the anticipated further development of this system, the utility of these data will be enhanced. They promise to be useful to planners in several areas and are already fulfilling parts of their promise.

TRANSPORTATION OF HAZARDOUS MATERIALS

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ABSTRACT

This presentation summarizes the fire-related data derived from hazardous materials(HM) incidents reported to the Materials Transportation Bureau, Research and Special Programs Administration, U. S. Department of Transportation, over the past several years. Discussed next are the research and development projects related to fire and actions undertaken to assist fire and other emergency services in dealing with HM transportation emergencies. These efforts deal with flammability/combustibility(e.g., hazard classification, risk assessment and emergency response planning/training), as well as to other hazards. The final portion consists of some conclusions and recommendations.

PREFACE

Thank you, Mr. Chairman. Ladies and gentlemen, it is a pleasure to be here and share with you some information on fire safety. One has to be encouraged at the obvious awareness of many aspects of the fire problem, professional and public interest and the progress that has been made in fire technology. However, we have a long, long way to go before the fire problem is under control.

Within the Department of Transportation(DOT), through the Research and Special Programs Administration and intermodal interfacing, there is a genuine effort to coordinate the research programs in fire and other safety areas. All of us here know how very difficult this is to accomplish, even when everyone is in favor of such cooperation and coordination. The individual work load is staggering and many interruptions leave little time for a person to address some of the major problems. The fire problem, like others, is compounded by the confusion that often results when

several Government agencies have overlapping legislative authorities and responsibilities. One only has to observe the difficulties encountered by the National Fire Prevention and Control Administration (now the Federal Emergency Management Agency), in trying to coordinate a national fire prevention and control program, to realize how tough the problem is. Nevertheless, we must all continue to improve and strive to make all our efforts mesh. As is true in every endeavor, effective communication (this conference is one such medium) is the key to success. As a start in that direction, this paper provides a few fire related statistics covering the past several years with respect to HM transportation. Next is a discussion of the Materials Transportation Bureau (MTB) HM research and development (R&D) efforts related to fire technology and emergency response areas. Brief conclusions and recommendations follow.

STATISTICAL DISCUSSION

Perhaps a few incident data can help to indicate the magnitude of the fire problem in HM transportation, at least in a general manner. Table 1 tabulates the data for the period 1974-1979 from fire/explosion incidents reported to the MTB in accordance with Section 171.16, Title 49 Code of Federal Regulations. These figures show that about one-half of the deaths and injuries occurred when both fire and explosion were involved, with a somewhat lesser number of both when only fire was experienced. These deaths and injuries do not appear large when compared to highway automobile accidents. However, with HM, there is always a potential for very serious accidents with some commodities and the public involuntarily is not willing

Table 1

HAZARDOUS MATERIAL INCIDENTS INVOLVING
FIRES AND/OR EXPLOSIONS--1974-1978 INCLUSIVE (JAN.-SEPT. 1979)*

| <u>Commodity Involvement</u> | <u>No. of Incidents</u> | <u>Deaths</u> | <u>Injuries</u> | <u>\$Damage</u> |
|----------------------------------|-----------------------------|---------------|-----------------|---------------------------|
| Fire | 113(20) | 1(0) | 12(127) | 2,619,055 (265,478) |
| Explosion | 14(2) | 3(2) | 12(1) | 189,680 (287,000) |
| Fire and explosion | 56(6) | 29(0) | 95(17) | 4,879,294 (832,000) |
| Spillage and fire | 435(69) | 48(9) | 344(61) | 18,442,292 (3,408,565) |
| Spillage and explosion | 20(3) | 6(0) | 211(2) | 435,208 (8,000) |
| Spillage, fire and explosion | 59(12) | 35(0) | 584(22) | 12,947,311 (743,164) |
| Total | 697(112) | 122(11) | 1,258(230) | 39,512,840 (5,544,207) |

* 1979 figures are in parentheses. All data are derived from the MTB Hazardous Materials Incident Reporting System(HMIRS).

to accept the hazards of HM transportation on the same basis as those from automobile driving. Therefore, we must work toward zero deaths, injuries and damage. It needs to be pointed out that the damage figures are very conservative. Actually, they may be off by an order(s) of magnitude, when one considers the results of litigation and the many other cost impacts(e.g., insurance, lost income, inconvenience, bad publicity). We see here only the tip of the iceberg. Spillage effect is obvious in the damage category, especially. Table 2 shows some interesting data on a few incidents which involved fires. One surprise is gasoline having

Table 2

SELECTED HAZARDOUS MATERIALS INVOLVED IN FIRES--
1974-1978, INCLUSIVE*

| Selected Commodity | No. of Incidents | | | | | | Deaths | Injuries | \$Damage |
|--------------------------------|------------------|-----|-----|----|---|-----|--------|----------|------------|
| | A | HH | HP | R | W | O** | | | |
| Acetylene | | | 4 | | | | 0 | 0 | 1,607 |
| Anhydrous ammonia | | | 1 | | | | 0 | 2 | 65,000 |
| Calcium hypo-chlorite mix. | | 5 | 2 | 1 | | | 0 | 1 | 97,000 |
| Compressed gas, n.o.s.(Flam.) | | 8 | | 2 | | | 2 | 43 | 391,813 |
| Crude oil petroleum | | 4 | 6 | | | | 5 | 4 | 855,000 |
| Flammable liquid, n.o.s. | 1 | 9 | 1 | 2 | | | 1 | 98 | 344,160 |
| Flammable solid, n.o.s. | | 1 | 1 | 2 | 1 | | 2 | 7 | 16,300 |
| Gasoline | 2 | 107 | 105 | 6 | | | 48 | 108 | 14,270,995 |
| LPG | | 12 | 21 | 32 | | | 48 | 559 | 13,373,271 |
| Paint, varnish, lacquer, stain | | 17 | 3 | | 1 | | 0 | 1 | 2,162,879 |
| ***** | | | | | | | | | |
| All commodities | | | 663 | | | | 113 | 1,035 | 38,887,952 |

*All data are derived from the MTB HMIRS.

**A--Air; HH--Highway(for hire); HP--Highway(private); R--Rail;
W--Water; O--Other.

no more deaths and only 20 percent as many injuries as LPG, when it has been commonly voiced that gasoline is the worst HM from the absolute standpoint. The general groups designated n.o.s.(not otherwise listed by name in Section 172.101, Title 49 CFR) commodities account for about four percent

of the deaths, but about 15 percent of the injuries. This is significant enough to warrant further scrutiny. The 1973 Logan Airport crash, not included in these statistics, should be mentioned, because it is a clearcut example where a common HM, nitric acid, was the immediate cause of a serious fire incident--the acid ignited sawdust, an unauthorized cushioning material.

This paper is confined to HM shipped via rail, highway, marine and air modes. However, a few data from the pipeline mode might be of interest. These figures come from pipeline liquids incident reports submitted to MTB in accordance with Section 195.54, Title 49 CFR. Figures represent all the incidents for that particular commodity, not just those involving fire, so it is not possible to make a direct comparison with data on the same commodities shipped via the other four modes. Table 3

Table 3
1978 PIPELINE INCIDENTS INVOLVING
SELECTED LIQUID COMMODITIES*

| <u>Selected Commodity</u> | <u>No. of Incidents(% of total)</u> | <u>Deaths</u> | <u>Injuries</u> | <u>\$Damage(% of total)</u> |
|---------------------------|-------------------------------------|---------------|-----------------|-----------------------------|
| Crude oil | 148(57.6) | 0 | 3 | 2,678,484(43.9) |
| Anhydrous ammonia | 1(.4) | 0 | 0 | 2,000(0) |
| Gasoline | 45(17.6) | 0 | 3 | 72,175(1.2) |
| LPG | 25(10.2) | 3 | 4 | 3,127,293(51.3) |
| ***** | | | | |
| All commodities | 255(100.0) | 3 | 10 | 6,095,361(100.0) |

*Data are derived from pipeline liquids incidents reported to MTB.

information indicates a relatively low number of deaths and injuries compared to other modes, as shown in Table 2--remember that we can not directly compare the two. However, LPG has the worst record in both cases. Table 4 is included to give an idea of the total number of pipeline liquids

Table 4

SUMMARY OF SELECTED PIPELINE LIQUID COMMODITY INCIDENTS--
1970-1978*

| Selected Commodity | No. of Incidents | | | | | | | | |
|-----------------------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| | 78 | 77 | 76 | 75 | 74 | 73 | 72 | 71 | 70 |
| Crude oil | 148 | 141 | 126 | 138 | 166 | 157 | 193 | 170 | 219 |
| Anhydrous ammonia | 1 | 1 | 3 | 3 | 2 | 1 | 0 | 4 | 2 |
| Gasoline | 45 | 40 | 37 | 42 | 29 | 48 | 57 | 49 | 61 |
| LPG | 45 | 20 | 13 | 25 | 26 | 22 | 16 | 44 | 25 |
| ***** | | | | | | | | | |
| All Commodities | 855 | 237 | 212 | 254 | 256 | 273 | 306 | 310 | 351 |

* Data are derived from pipeline liquids incidents reported to MTB.

incidents reported by year over a nine-year span. It is difficult to find any trends in these data. Possibly gasoline incidents show a slight decreasing trend. Now let us take a look at some R&D efforts.

RESEARCH DISCUSSION

Among the types of materials defined as hazardous by DOT,^{1/} six rather obviously imply a fire hazard. These are Combustible liquid, Flammable solid, Compressed gas, n.o.s.(Flammable gas), Flammable liquid, Organic peroxide and Oxidizer. Two others--Class B explosives and Class C

^{1/} Title 49, Code of Federal Regulations, Parts 100-199, Revised as of October 1, 1978.

explosives--contain numerous materials or items which have very potent flammable characteristics. We recognize also that fire may not be the only hazard of a particular commodity in any of the eight classes.

During the past ten years, the MTB and its predecessor hazardous materials Offices have sponsored projects to evaluate, modify or develop new laboratory test methods for determining the hazard classification of chemical substances and to establish the related classification criteria for transportation purposes. The U. S. Bureau of Mines(BuMines) Safety Research Center developed the basis^{2/} for the DOT to change the HM Transportation Regulations fo specify the Tag closed tester in place of the Tag open tester for determining flash points for flammable liquids. Other closed testers also have been authorized.

With respect to the Flammable solid(FS) class, the BuMines^{3/} developed the following test methods: a rotating disc time-to-ignition test for determining the ease of ignition; a horizontal flame spread-rate test; and for pyrophoric materials, an ease-of-ignition maximum heat rise test in a high-humidity environment. Flammable, highly flammable and extremely flammable subclasses were proposed based upon a combination of test results.

In the Oxidizing materials(OM) part of the study, the BuMines^{4/} developed a horizontal burning rate test(a bed of solid oxidizer-red oak sawdust

^{2/} Kuchta, J.M., U. S. Bureau of Mines, "Recommendations of Flash Point Method for Evaluation of Flammability Hazard in the Transportation of Flammable Liquids"(1970)(NTIS Accession No. PB 193077).

^{3/} Kuchta, J.M., U. S. Bureau of Mines, "Classification Test Methods for Flammable Solids"(1972)(BuMines RI 7593).

^{4/} Kuchta, J.M., Furno, A.L., and Imhof, A.C., U. S. Bureau of Mines, "Classification Test Methods for Oxidizing Materials"(1972)(BuMines RI 7594).

mixture), and an unconfined spontaneous ignition(or maximum heat rise) test for gaseous and liquid oxidizers. Again, several categories of OM's were proposed based upon combinations of test results.

In a special report^{5/} the BuMines describes an experimental technique and test data for classifying materials in terms of their reactivity with water. These chemicals are a special group within the FS class. The report also includes an experimental comparison of the BAM(steel tube with orifice) and RVO-TNO(pressure vessel with diaphragm) tests for evaluating thermal decomposition sensitivity of organic peroxides(OP), fire being one potential hazard of such decomposition. The card gap, differential thermal analysis, solid impact and friction tests are discussed as possible additional tests for use in hazard classification of OP.

The General Electric Company(GE) was tasked to evaluate the reproducibility of the BuMines methods and test results. Results^{6/} were in agreement in some cases, but gave evidence that there could be significant discrepancies and showed a need to examine several influencing variables more closely than had been done previously(e.g., humidity effect on and moisture content of sawdust, sawdust-to-oxidizer ratio, particle size distribution, bed size, heat flux of the burner ignition source, degree of confinement and bed support structure). Most of these related primarily to the solid oxidizer test. Modifications were made in the test ap-

^{5/} Mason, C.M. and Cooper, J.C., U. S. Bureau of Mines, "Classification of Hazardous Materials--Water Reactive Materials and Organic Peroxides" (March 1972)(NTIS Accession No. PB 209422).

^{6/} King, P.V. and Lasseigne, A.H., General Electric Company, "Hazard Classification of Oxidizing Materials and Flammable Solids for Transportation - Evaluation of Test Methods"(May 1972)(NTIS Accession No. PB 220084).

paratuses also. Considerable alterations were made in the thermal ignition test for gaseous and liquid oxidizers and in the hygrothermal ignition sensitivity test for flammable solids. GE also tested some additional OM's and FS's. In a second phase study,^{7/} GE made further refinements in the OM and FS test methods and recommended hazard classification criteria, tested other materials, provided a preliminary evaluation of hazard classification tests for a Flammable liquid(FL) and recommended those tests which should be further studied with respect to FL's.

The Naval Ordnance Station, Indian Head, Maryland, reported results^{8/} on its contract to reassess both the BuMines and GE recommended test methods and criteria for OM's and FS's, with particular emphasis being placed on further identification and control of those variables/factors which cause poor reproducibility in test results. In the interim, work has continued at a reduced pace, due to a priority study on non-solid explosives classification testing. Among the methods investigated, but not yet reported, have been a confined(excelsior in a vented wooden box) test for liquid oxidizers and a larger-scale solid oxidizer-sawdust test (conical pile) than the horizontal bed test. The former was intended to permit establishment of the boundary line between the material being an oxidizer or corrosive material(e.g., nitric acid concentration). Both methods had been utilized by the Bureau of Explosives, Association of American Railroads.

^{7/} Hough, R., Lasseigne, A. and Pankow, J., General Electric Company, "Hazard Classification of Flammable and Oxidizing Materials for Transportation - Evaluation of Test Methods, Phase II"(April 1973)(NTIS Accession No. PB 227019).

^{8/} Dale, C.B., Naval Ordnance Station, Indian Head, Maryland, "Classification of Oxidizers and Flammable Solids, Phase III"(March 1975)(NTIS Accession No. PB 240878/AS).

The Naval Surface Weapons Center(NSWC)(formerly the Naval Ordnance Laboratory)(NOL), White Oak, Silver Spring, Maryland, reviewed the information on spontaneously combustible solids including pyrophoric--air-hazardous materials and water-reactive materials and reported pertinent data^{9/} on the following: the causes and prevention of spontaneous combustion in organic and inorganic materials due to air and water reactivity; the application of various mathematical treatments to spontaneously combustible materials; and available test methods for assessing the flammable properties of such materials. In the interim, some work, not yet published, has been directed toward the development of an adiabatic storage test procedure.

Although fire is not the only concern, it is certainly one real potential hazard from thermally unstable materials. The NOL^{10/} searched the literature and conducted thermal sensitivity measurement on a number of organic and inorganic compounds listed in the DOT HM Transportation Regulations^{1/}. The laboratory tests involved thermal surge stimuli, differential scanning calorimetry and a system designed to determine quantitatively the percent decomposition of liquid and solid materials at the limiting parameters of one-hour duration and 300°C. Thermal instability studies^{11,12/} aimed at developing meaningful classification test procedures

9/ Kayser, E.G. and Boyars, C., Naval Surface Weapons Center, White Oak, Silver Spring, Maryland, "Spontaneously Combustible Solids--A Literature Survey"(May 1975)(NTIS Accession No. PB 244046).

10/ Kayser, E.G., Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland, "The Thermal Decomposition of Thirty Commercially Available Materials at 300°C."(February 1974)(NTIS Accession No. AD 783960).

11/ Tsang, W. and Domalski, E.S., National Bureau of Standards, "An Appraisal of Methods for Estimating Self-Reaction Hazards"(June 1974)(NTIS Accession No. COM-74-11658/3WK)

12/ Domalski, E.S., National Bureau of Standards, "A Second Appraisal of Methods for Estimating Self-Reaction Hazards"(March 1977)(NTIS Accession No. PB 266925).

and criteria, have been completed by the National Bureau of Standards, with completion of ongoing work and definitive recommendations expected in 1980.

The University of Southern California^{13/} evaluated a number of risk analysis methods, adapted one mathematical approach for assessing the risks of transporting HM and illustrated the method, using reported incident data for LPG and for parathion and methyl parathion. Flammability of the former was one parameter considered in the risk assessment. The method was subsequently computerized and tied into the MTB HMIRS.^{14/} ORI, Inc., has completed a comparative risk analysis^{15,16/} of air versus other modes for shipping Class A explosives and flammable liquid cryogenics. A great deal of emphasis has been placed on the fire hazards of the latter, especially.

The Coast Guard conducted for MTB a series of tests in which steel and plastic drums, filled with flammable liquids, were subjected to external fires.^{17/} As expected, the plastic drums did not exhibit the violent bursting behavior that the steel ones did.

^{13/} Jones, G.P., University of Southern California, "Volume I, Risk Analysis in Hazardous Materials Transportation"(March 1973)(NTIS Accession No. PB 230810/AS).

^{14/} Philipson, L.L., University of Southern California, "A Mechanism for Interfacing the Risk Analysis Model with the Hazardous Materials Incident Reporting System"(Sept. 1974)(NTIS Accession No. PB 239859/AS).

^{15/} Kloeber, G., Cornell, M., McNamara, T. and Moscati, A., ORI, Inc., "Risk Assessment of Air Versus Other Transportation Modes for Explosives and Flammable Cryogenic Liquids, Volume I: Risk Assessment Method and Results"(Sept. 1979)(Report not finalized).

^{16/} Ibid., "Volume II: Supporting Documentation"(Sept. 1979)(Report not finalized).

^{17/} U. S. Coast Guard, "Fire Exposure Tests of Polyethylene and Steel Fifty-five Gallon Drums Loaded with Flammable Liquids, Phase II"(1977)(NTIS Accession No. PB 283488/AS).

There is a project underway at Southwest Research Institute which should be of interest. This is directed toward developing new approaches for controlling the behavior of compressed, liquefied flammable gases released from ruptured bulk containers. It entails analyzing the accident data, determining the real influencing factors, evaluating the success of previously suggested improvements/modifications, devising new approaches and validating the most promising candidates by actual field tests. The work is scheduled for completion in 1981.

EMERGENCY RESPONSE DISCUSSION

As an aid to the emergency services(fire is one) and others concerned with planning against and successfully handling HM transportation emergencies, MTB has taken several significant actions. Thru NTIS, the Chemical Propulsion Information Agency(Johns Hopkins University Applied Physics Laboratory) has been tasked to revise and expand the current hazardous materials emergency action guide^{18/} which has been serving firemen and many others in several versions, for several years, as a valuable guide on fire hazards, danger areas and recommended actions for a number of common bulk chemicals.

The National Fire Protection Association(NFPA) produced for MTB in 1978 a 20-hr. self-standing, slide-tape training course entitled, "Handling Hazardous Materials Transportation Emergencies." In 1979, NFPA developed a supplemental course entitled, "Handling Pipeline Transportation Emergencies." NFPA has been tasked to convert the first four units(these

^{18/} U. S. Department of Transportation, National Highway Traffic Safety Administration and Materials Transportation Bureau, "Emergency Action Guide for Selected Hazardous Materials(1978).

deal with characteristics, identification and obtaining technical assistance) of the eight-unit HM course into a home-study/correspondence-type course, especially aimed at the individual fireman

Canyon Research, Inc., has nearly completed development of a training course entitled, "Handling Transportation Emergencies Involving Radioactive Material," which will be of great value to the fire services and many others.

MTB recently has funded two projects which should be of interest to the fire community, namely, one with the State of Colorado highway group for assisting in establishing a HM training academy and the other with the Puget Sound Council of Governments for investigating the transportation of HM within that area and developing a comprehensive, representative plan for managing HM transportation, including emergency response planning.

Both the HM and PL courses are available for purchase from NFPA and seminars are scheduled by NFPA. For additional information as to the availability of these and other courses and details on the two projects, you might want to contact the MTB Information Services Division(202/426-2301).

MTB is committed to actively assisting the fire services and others who must deal with HM and PL transportation emergencies. A number of organizations share this concern and are making contributions. One of these, the Association of American Railroads-Chemical Manufacturers Association Inter-Industry Task Force on the Rail Transportation of Hazardous Materials, has available a five-hour awareness course entitled, "Recognizing and Identifying Hazardous Materials." The Task Force has an ambitious plan for a number of industry teams to present the course throughout the nation

over the next couple years.

CONCLUSIONS AND RECOMMENDATIONS

From the fire standpoint on an absolute basis, gasoline approaches LPG as the worst hazardous material, yet this does not evoke the same kind of outcry or action as do the spectacular LPG and propane tank car accidents. Why? This appears to stem from a public attitude/mentality which is unable or unwilling to look at a hazard/safety situation objectively, or to put things in proper perspective. There is a real need to look at the HM fire problem from a total system standpoint. This means looking at: all types of commodities which can create/enhance fires; packagings/ container designs; shipment quantities; modal characteristics; public attitudes; demographic factors; emergency response capabilities; and safety-risk-economic benefits to name a few that come to mind. It is still going to be up to those individuals, such as attendees here, involved with fire safety to: maintain close contact with colleagues; exchange ideas, data, reports, training courses/materials and research plans; supply input to the technical information systems; and participate in topical meeting like this one and convince management of their value, so that travel funding for such purposes is budgeted.

Progress has been made in understanding the nature of the fire problems. However, much remains to be done. Dedication, hard work and cooperation, sweetened with an abundance of dollars, can do much toward reaching the final objective--no serious fire problems.

Thank you for your interest and attention.

HIGHWAY TRANSPORTATION OF HAZARDOUS MATERIALS
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Ours is a highly complex agricultural and industrialized nation. We use large quantities of chemicals, many of which are hazardous materials. Many times we hear special interest groups advocating banning or limiting the transportation of hazardous materials. Few people really realize how essential hazardous materials are to their everyday lives. Radioactive materials are essential to many modern medical techniques: poisons are used in agriculture and medical applications; corrosives start your automobile; and there is the flammable so essential to the modern day American, gasoline that powers the automobile and gives us the freedom and mobility we know.

The Department of Transportation is the agency of the Federal government responsible for transportation safety, including the transportation of hazardous materials. The Federal Highway Administration's Bureau of Motor Carrier Safety (BMCS) is the element responsible for the administration and enforcement of the Hazardous Materials Regulations applicable to shippers and carriers by highway. The Hazardous Materials Regulations are found in the Code of Federal Regulations, Title 49, Parts 100-199.

The Bureau's duties include the development and revision of rules and regulations governing the qualifications and hours of service for motor carrier employees; the safe operation and maintenance of motor carrier

vehicles; the safe transportation of cargo, bus passengers, and migrant workers; the recording and reporting of accidents; the safety of drivers; and the administration and enforcement of the rules and regulations governing the packaging, marking, loading, and transportation of hazardous materials.

The Bureau is relatively small in size, having an authorized field staff of 172 persons to administer the Federal Motor Carrier Safety Regulations and the Department's Hazardous Materials Regulations to approximately 150,000 motor carriers of property and 20,000 entities who ship hazardous materials, many of whom may operate 100 or more shipping facilities or terminals. In each of the nine regions, there is one Hazardous Materials Specialist, whose primary duties are to keep abreast of problem areas involving hazardous materials' shippers and carriers in his assigned region.

Flammables, both liquid and gaseous, when released from their containers, probably pose the greatest hazard to people and property of all the classifications of hazardous materials. They vaporize (and thereby become highly explosive), disperse readily, are easily ignitable, and oftentimes cannot be controlled by emergency response teams.

Flammables are transported in both bulk and small quantities, small quantities being the familiar drum, pail, or can. Bulk quantities are containers of 110 gallons capacity or more.

Bulk quantities are transported in portable tanks and cargo tanks. A portable tank is defined by the Hazardous Materials Regulations as a container of 110 gallons or more capacity, designed to be loaded into

or on, or temporarily attached to a transport vehicle, and equipped with skids, or mountings to facilitate handling by mechanical means. The portable tank is becoming a very popular container, particularly in international trade.

Cargo tanks are containers permanently attached to or forming a part of any motor vehicle, or because of its size or construction or attachment to a motor vehicle is loaded or unloaded without being removed from the vehicle. The cargo tank probably transports more flammables than any other container.

The Federal regulations provide requirements which a shipper shall meet when packaging and preparing a material for transportation, provide rules as to how the carrier shall handle and care for the material during the transportation, and requirements for vehicles and drivers.

These Federal regulations provide hazard communication requirements for the protection of handlers, the public, and particularly for emergency response personnel. These require the vehicle to be placarded on the front, rear, and both sides of the cargo body with the appropriate placard for the material being transported. The front placard may be displayed on the front of the power unit or on the front of the cargo carrying body. The placards must be securely affixed or placed in a holder; be clear of appurtenances and devices such as ladders, pipes, doors, and tarpaulins; and located so dirt or water is not directed to them from the wheels of the vehicle. They must not be located near any advertising or other marking that would substantially reduce their effectiveness and the wording must be displayed horizontally-reading left to right.

Cargo tanks are required to remain placarded even though empty until cleaned of any remaining material or refilled with a non-hazardous material.

A second communication requirement is the shipping paper. The driver of the vehicle is required to have in his possession a shipping paper which shows the quantity, shipping name, and hazard classification of the material.

The carrier and driver are required to ensure the shipping paper is available and readily recognizable by authorities in the event of an accident or inspection. Specifically the paper shall be clearly distinguished, if carried with other papers, by either distinctively tabbing, or by appearing first. The shipping paper shall be stored by having it within the driver's reach when secured by his seat belt, and either readily visible to a person entering the driver's compartment or stored in a holder mounted inside the door on the driver's side of the vehicle. When the driver is not at the controls, the shipping paper shall be in the holder or on the driver's seat of the vehicle.

The Federal regulations have yet a third communication requirement whereby the package or container itself is required to be labeled with a prescribed label that represents the hazard of the material contained in the container.

The Materials Transportation Bureau has another communication requirement in the rulemaking process at this time. This proposed rule would require cargo and portable tanks to be marked with a distinctive number, which is

assigned to a particular commodity. It is proposed to publish an emergency response guide providing information on how to handle emergencies involving materials to which the number is assigned. This proposal would adopt the present United Nations Commodity Numbering System.

The Federal regulations impose requirements on the shippers of hazardous materials. The shipper must package his material in the container specified in the regulations for that material. The package must be labeled and otherwise marked as to the hazard classification of the material.

A shipping paper must be prepared and furnished to the motor carrier. The paper must be prepared in a prescribed format and show the quantity of the material by weight or volume, the shipping name prescribed in the regulations, and the hazard classification of the material. The shipper must certify the material has been properly described, marked, labeled, packaged, and in proper condition for transportation. The shipper must have on hand and make available to the motor carrier the proper placards for the material being shipped.

Experience has shown that if the shipper has the shipment in compliance when shipped, the transportation has a good chance of being completed without a violation of the regulations or an incident occurring.

The Federal regulations prohibit the carrier from accepting a shipment of hazardous material for transportation unless the shipper has complied

with regulatory requirements. These regulations require the carrier to properly load the shipment, block and brace it to prevent movement, and to placard the vehicle. The carrier and driver are required to properly store and have available the shipping paper.

The Federal Motor Carrier Safety Regulations found in the Code of Federal Regulations, Title 49, Parts 390-398, provide requirements for drivers of vehicles transporting hazardous materials. As an example, drivers of vehicles transporting flammables are required to stop for railroad crossings and are prohibited from smoking within 25 feet of the vehicle. These same regulations also prescribe where the vehicles are to be parked and routes to be used.

This country uses over 290,000,000 gallons of motor gasoline every day, most of which, sometime between the wellhead and the service station, will be transported in a cargo tank upon a public highway. To put this amount in perspective, consider that a tractor semitrailer cargo tank, 55 feet long, will transport approximately 8,500 gallons. The total volume is over 34,000 cargo tank loads every day, and if placed end to end would extend from Kansas City, Missouri, nearly to Oklahoma City, Oklahoma.

Federal regulations provide requirements which newly constructed cargo tanks to transport flammables must meet when manufactured, and to which they must be maintained while in service.

Cargo tanks must be constructed of specific materials, of specified thicknesses, welded in a specific manner, and supported, anchored, and reinforced as prescribed.

Product discharge openings must be equipped with internal valves, which must be designed with shear sections, so when downstream piping is damaged, the valve seat will be retained in the compartment or tank in a closed position without damage to the compartment or tank. Discharge valve operating controls must have a remote closing control, which is generally located at the front of the cargo tank. The operating controls must also be equipped with a heat sensitive device which will close the discharge valve at a temperature of 250 degrees Fahrenheit.

Cargo tank compartments for transporting flammables must be equipped with venting which must meet specific requirements.

Closures for filling, manhole, or inspection openings shall be protected from damage that would result in leakage in the event of overturn of the vehicle, by enclosing them within the body of the tank or a dome attached to the tank, or by guards.

Manufacturers are required to mark new cargo tanks with a certification plate which tells who the manufacturer is, the specification to which the tank is constructed, the material, capacities, operating pressures, and date of manufacture and test.

Cargo tanks used to transport flammable liquids are required to be visually inspected every 2 years by a responsible and experienced inspector for compliance with the Federal Hazardous Materials Regulations,

and compliance with the specification to which it was originally constructed. This inspection shall be for corroded areas, bad dents, weld defects, defects in piping, valves, and gaskets, and other conditions including weakness that might render the tank unsuitable for service.

Hydrostatic testing is to be performed if the tank has been out of service for 1 year or more, or involved in an accident in which the tank may have been dented, torn, or otherwise damaged so as to affect its product retention integrity. Test and inspection dates are then required to be marked on the tank near the certification plate. This certification plate is usually found in the area of the right front corner.

When the volume of flammables transported by cargo tanks without incident is considered, the cargo tank has an exceptional safety record. However, its size and the quantities involved present the potential for disaster, should a release of contents occur.

For some time the BMCS has been concerned about the product retention capabilities of cargo tanks involved in accidents. Incident reports filed with the Materials Transportation Bureau show that only 20 percent of the unintentional releases of flammables involve vehicle accidents. However, these vehicle accidents account for 61 percent of the reported fires.

This growing concern has caused the BMCS to undertake a research study to assess the existing specifications for cargo tanks to identify items which represent potential leakage points in accidents. This study will also assess present maintenance practices and requalification requirements

as they affect cargo tanks' continued product retention capability. From this study could emerge rule change recommendations to the Materials Transportation Bureau.

The BMCS administers the Hazardous Materials Regulations to carriers and shippers through a program of education, inspection, and enforcement.

BMCS personnel are continuously presenting hazardous materials seminars in an attempt to better educate the carrier/shipper and emergency and regulatory personnel involved in hazardous materials transportation. Through these efforts, the Bureau believes progress has been made towards reducing hazardous materials accidents.

The BMCS conducts compliance surveys of carrier and shipper operations. Shipper facilities are inspected to ensure shipments are placed in the proper containers, properly labeled and marked, and the proper shipping documentation prepared.

Compliance surveys are also conducted of carrier operations. Records are checked to determine driver's hours of service, qualification of drivers, that accidents are recorded and reported, and carrier's inspection and maintenance practices monitored.

Those carriers using cargo tanks must also have on file the manufacturers certificates of compliance and data sheets and records of periodic inspection and testing.

Another important inspection activity is the roadside driver/vehicle inspection. In conjunction with local officials, check points are periodically set up on an unannounced basis to inspect vehicles in operation. In conducting these inspections all parts and accessories necessary for the safe operation of the vehicles are inspected and the driver and vehicles inspected for compliance with the Hazardous Materials Regulations. If a vehicle's condition is found to be "imminently hazardous" or is likely to result in an accident or breakdown, it is declared "out of service" on the spot. The vehicle cannot be driven until the violation is corrected.

Specific violations for which a cargo tank may be placed out of service are: leaking compartments; no placards; inoperative or open valves; defecting or leaking fill opening gaskets or covers.

Violations of the Hazardous Materials Regulations are investigated to develop evidence for enforcement actions. In addition to court actions, the Bureau itself can initiate actions which result in civil penalties.

All of the States have entered into cooperative agreements with BMCS with respect to motor carrier and hazardous material safety. Many States and local jurisdictions have adopted the Hazardous Materials Regulations as a whole, or in part, for application in their interstate commerce.

The BMCS through cooperation with State and local governments will continue to emphasize the safe transportation of hazardous materials.

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B A Y A R E A R A P I D T R A N S I T D I S T R I C T

F I R E I N T R A N S B A Y T U B E

J A N U A R Y 1 7 , 1 9 7 9

EMMET D. CONDON

On Wednesday, January 17, 1979, at 4:30 p.m., Train 363 proceeding westbound in the Transbay Tube (TBT), came to an emergency stop and reported a possible fire onboard and smoke at Milepost (MP) 4.8 on the M-1 track. The emergency stop resulted from a derail bar being broken when struck by a metal line switch box cover which was improperly secured and had fallen from the train. With a technician onboard Train 363, the problems were apparently corrected; and the train exited the TBT, eventually completing its trip to Daly City.

Due to the incident, the two following trains were instructed to proceed through the TBT at a slow speed and make a visual inspection of the M-1 track. Except for locating the broken derail bar, these "sweep" trains found no reason for the problem on Train 363. Normal service was then resumed on the M-1 track, and seven additional trains proceeded through the TBT on the M-1 track without incident.

At approximately 6:00 p.m., Train 117 (Fire Train) departed the Oakland West Station with forty (40) passengers, and proceeded through the TBT toward the Embarcadero Station - San Francisco. At 6:06 p.m., train operator Robert Law reported to BART Central (Central) from the TBT that he had a bad overload, possible fire, and smoke coming through the train.

Misalignment of the third rail and/or third rail protection board brackets occasioned by impact of the line switch box cover from Car 537 - Train 363 caused the breaking of contact shoe assemblies on Train 117, resulting in short circuits and fire.

The forty (40) passengers aboard Train 117 immediately moved toward the lead end (S.F.) of the train, away from the rear of Train 117 where the fire had occurred. Paul Gravelle, a BART Line Supervisor, was fortunately onboard and able to assist the passengers during the emergency.

Smoke immediately enveloped the train and prevented the train operator from reporting his location to Central. As a result of the fire and explosion, the train had made an automatic emergency stop at a point later determined to be approximately one mile west of the Oakland Vent Structure. Central, in an effort to alleviate the smoke conditions and vent the M-1 bore, and without the knowledge of the train's precise location, incorrectly opened the damper located directly west and in front of the train, drawing more smoke through and around Train 117.

At 6:09 p.m., Central notified the Oakland Fire Alarm, requesting Oakland Fire Department (O.F.D.) response to Maintenance Way 04 near the Oakland West Station, stating that there was a train

with a smoke problem in the TBT on the Daly City side. Confusion about fire location ensued between Central and Oakland Fire Alarm, resulting in the incorrect dispatch of O.F.D. responding units to Oakland West Station. Previous to this call, Central had contacted the San Francisco Fire Department (S.F.F.D.), thinking it was the O.F.D. S.F.F.D. was instructed by Central to disregard the call. Central's emergency operations procedure did not specifically require notification of both fire departments in the event of an incident in the TBT.

The O.F.D. responded to the Oakland West Station, believing that the involved train was at that location. When they discovered that the fire train was in the TBT, nine (9) firemen were sent into the tube on Train 900 (Rescue Train) to assist in evacuating the passengers. It was then necessary to dispatch additional fire units to the Oakland Vent Structure as required by O.F.D.'s regularly established response plan for incidents in the TBT. Central was unaware of the proper Oakland response. Ten (10) firemen, including Lieutenants Elliott and Schuette, entered the Oakland Vent Structure and proceeded toward the scene of the fire to assist in rescue and fire suppression. All men were equipped with one-half hour MSA oxygen breathing apparatus, and all were walking except two men who rode a golf cart loaded with equipment.

At approximately the same time, Central dispatched Train #111 (Evacuation Train) loaded with 1000 to 2000 passengers into the M-2 tube from Embarcadero Station to evacuate the forty passengers on the fire train.

On the fire train Gravelle and Law had unsuccessfully attempted to uncouple the burning cars in an effort to remove the remainder of the train with the passengers to Embarcadero Station. Central had started the ventilation exhaust system as soon as an approximate location of the train was determined from the Central Control board; unfortunately, the wrong blast damper was opened in front of the train. The resulting envelope of smoke prevented passenger evacuation from the train. Gravelle tried to leave the train and reach an emergency door to the gallery, but he had to re-enter the train and report to Central that he could not breathe outside of the train.

When Central became aware of the fact that the ventilation system was not clearing the train properly, other blast dampers at the rear of the train were opened. However, the passengers were to remain trapped on the train by the dense smoke until Gravelle reported to Central at 6:44 p.m. that they were getting some "clear sky." Simultaneously, the O.F.D. rescue team arrived, disembarked from Train 900 and commenced evacuation of the passengers through the central gallery to the evacuation Train 111 standing by on the adjacent M-2 track.

The passengers on Train 117 had been trapped for forty minutes in the heavy smoke, and the evacuation train had been positioned

in the opposite trackway for approximately thirty (30) minutes with over one thousand (1000) passengers onboard. Smoke had also entered the evacuation train and was distressing the onboard passengers. In response, Central opened several blast dampers in the M-2 trackway to try to clear the evacuation train.

When all passengers were safely onboard, Train 111 was released on automatic train operation and proceeded to Oakland West Station for evacuation and medical treatment of injured passengers and employees. The train acceleration of approximately three miles per hour per second caused a strong suction action in the gallery and trackway -- strong enough to knock several firefighters to the ground and tumble them about. The train action also sucked a large amount of smoke from the fire bore through the gallery and into the M-2 trackway.

When the Oakland firefighters recovered from this "shellacking", they closed the door between the gallery and the M-2 trackway. After assessing their position and the available firefighting equipment, they made the decision to walk out to the San Francisco side of the TBT.

During the passenger rescue operation, Lieutenants Elliott and Schuette, with their crews, had almost reached the location of the fire train when they began to encounter smoke that was dense enough to require them to don their breathing equipment. It was 6:45 p.m. by Lieutenant Schuette's watch, approximately the same time as Gravelle's report from the fire train that the smoke was clearing.

A combination of several things caused the heavy smoke to travel toward Oakland which engulfed the firefighters in the gallery. A door to the gallery from the fire bore had been inadvertently left open. The exhaust fans in the San Francisco Vent Structure had been turned off, and Central could not reactivate them. Several blast dampers had been opened indiscriminately. Additionally, train operation in the TBT had a significant effect on the movement of the smoke. These events, in combination with loose-fitting gallery doors and hatch covers, resulted in movement of smoke into areas of the ventilation system, ultimately trapping the Oakland firefighters in the gallery -- an area which they had been trained to believe was a safe refuge.

The smoke in the gallery area became so dense that there was no visibility; Lieutenants Elliott and Schuette, aware that their breathing apparatus were almost expended, made a decision to retreat. Shortly after they began retracing their steps, Lieutenant Elliott experienced breathing difficulties which became so severe that he removed his mask and almost immediately began to collapse. His fellow firefighters supported him and struggled down the gallery, alternately falling down and bumping into utility installations. Several members of the O.F.D. gallery unit

responded heroically in a futile effort to save Lieutenant Elliott.

All of the trapped firemen, except Firefighter Heath and Lieutenant Elliott, were eventually able to find their way out of the gallery, either by exiting through a gallery door opened by a BART employee and an Oakland firefighter, or by walking back to the Oakland Vent Structure. The performance of BART employee Padilla in assisting rescue efforts in the gallery can only be deemed heroic. Lieutenant Elliott and Firefighter Heath were finally removed from the gallery by an O.F.D. rescue team, and CPR was immediately initiated.

At 7:53 p.m., Train 377 was sent into the TBT from Oakland West Station in the M-1 fire bore to evacuate the injured firefighters. This train contained approximately 55 passengers, and neither they nor the train operator were informed by Central that they were proceeding into an emergency fire area. Central assumed that there were no passengers on the train since it had been delayed at the station for approximately one hour. However, Central did not verify this fact, nor did they inform the train operator that she was in anything other than regular revenue service.

Train 377 returned to Oakland West Station and the injured firemen, as well as several employees, were transported to various hospitals for medical attention. It was confirmed that Lieutenant Elliott had expired and that firefighter Heath was in serious condition.

The participation of the S.F.F.D. in the emergency was seriously delayed because Central failed to notify them to respond to the train fire. In fact, Central's response to S.F.F.D. requests for information referred simply to a train with a smoke condition. There appeared to be a reluctance on their part to acknowledge that a fire was in progress in the TBT. Finally, at 6:32 p.m., the Oakland Fire Alarm contacted the S.F.F.D. and asked them to respond to the TBT and standby, stating that there was a BART train on fire in the TBT approximately one mile from the Oakland West Station.

The S.F.F.D. dispatched fire department units to the Embarcadero Station and to the S.F. Vent Structure. The established S.F.F.D. plan called for one group to proceed to the fire in the gallery with a second group transported to the fire on a BART train, carrying the bulk of the necessary equipment.

The S.F.F.D. was unable to locate the portable phones stored in the Embarcadero Station, so most of their communications were conducted over the BART maintenance telephone line which was experiencing considerable difficulty.

At 6:45 p.m., the San Francisco Command Post ordered an emergency vehicle to be brought to the Embarcadero Station, and further

requested a BART train be brought to the M-2 trackway to move men and equipment to the fire. However, it was not until 7:10 p.m. that Train 901 arrived at the Embarcadero Station, and it arrived on the M-1 track rather than the M-2 track as requested. Central later stated that the reason for not complying with the Fire Department's request was their hope that they could couple the 901 train to the fire train and tow it to the Embarcadero Station. However, they did not communicate this information to the Fire Department.

Train 901 was loaded with men and equipment while the Command Post attempted to contact the O.F.D. to get a progress report. Communications were very poor on all telephone lines, particularly on the telephone lines between the S.F.F.D. and Central, as well as on the maintenance telephone.

At 7:52 p.m., Train 901 proceeded toward the fire until encountering loss of traction power at Milepost 5.4. At this point, the men on the train were joined by S.F.F.D. personnel walking in from the San Francisco Vent Structure. All equipment was off-loaded from Train 901, and the firefighters proceeded toward the fire. Shortly thereafter the combined S.F.F.D. unit met the Oakland firemen who were walking out from the fire scene toward San Francisco. S.F.F.D. personnel continued and carried their equipment approximately one mile before reaching the fire scene.

Fire suppression activities were initiated from the M-2 bore, through the gallery and then into the fire bore. Heat was so intense that firefighters had to be relieved at five-minute intervals, and it was necessary to keep them covered with secondary hose streams while they were operating in the fire bore.

Firefighting activity continued until sometime after 10:00 p.m. when control had been sufficiently established to permit a survey of the fire train. Fire had penetrated the floor in the second and third cars from the rear of Train 117 and then progressed throughout the interior of five of the seven cars, totally destroying them.

At 1:30 a.m., January 18, the TBT fire was finally declared under control by the San Francisco Command Post, and the arduous task of preparing and removing damaged and destroyed train cars commenced.

FIRE TESTING OF CABLE PENETRATIONS IN TELEPHONE BUILDINGS

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Abstract

A series of large-scale fire tests has been performed to determine the fire-resistance characteristics of cable-penetration firestops. These firestops are closure assemblies used in telephone buildings where communication and power cables, either as single cables or as bundles of cabling, penetrate floors or walls. The testing methods used ranged from liquid fuel pan fires to small and large-scale high-temperature furnaces. A comparison is made of the thermal characteristics of these test methods and of the influence of experimental parameters on the thermal behavior of the firestops. The measurement of the thermal gradients within multi-cable closure assemblies as a function of time and the reproducibilities of the test results are outlined. The use of thermal gradients to evaluate the effectiveness of the firestop closures is explored in an attempt to develop performance criteria.

Introduction

Within the Bell System there has evolved a variety of multipurpose cable openings which are used to traverse switchboard, power, or transmission cables, either as individual strands or as bundles of varying size, through the floors and walls of central offices. These openings exist as either rectangular or cylindrical holes ranging in dimension from several inches to many feet and containing cables emplaced from the 1920's until the present time. The cables themselves, ranging in diameter from 1/8" to several inches, contain electrical insulation material that has evolved from early cellulosic and rubber compounds to present-day heavily fire-retarded PVC and rubber formulations.

Bell Laboratories has been experimentally fire testing the cable-hole closures used to firestop such cabled openings since 1973; this paper examines some of the testing methods used to measure their fire-resistance properties. Many combinations of cabling and cable-closure designs have been examined, but, for the purpose of defining the variables existing within the test methods, the results given are for current production switchboard cables, i.e., with fire-retarded polyvinyl chloride insulation on the conductors and the cable sheathing, installed according to current Bell System Practices in a standard 2' x 1' floor opening firestopped by a vertis closure. The 2' x 1' opening is the predominant size used in equipment-room building bays to pass cable bundles from floor to floor.

The objectives of the program have been to develop reliable fire-testing procedures with which to assess the fire-resistance characteristics of cabled closures. Any fire test by itself should be reproducible and provide unambiguous data. For these reasons the tests reported in this paper have examined the effects of varying experimental parameters and have been heavily instrumented with thermocouples to provide a complete thermal history of test assemblies during the period of the fire test. Although some closures were subjected to fire tests using fuel loads such as 250 gallons of gasoline or 500 lb of polystyrene foam sheeting as rapid growth fire sources, and to slower-growth fires in equipment frames and in polyethylene cabling arrays, the majority of tests have used propane-fueled furnace conditions.

With the establishment of reproducible standard test conditions the closures' fire resistance properties have been defined within the context of four characteristics:

1. The structural integrity of the closure and its contents over the period of a fire test
2. Whether open-flaming conditions penetrate through the closure assembly from the fire zone or occur by self-ignition at the cable bundle surface on the non-fire-exposed side of the closure
3. The thermal gradients developed throughout the closure and cable bundle over a two-hour test period in terms of the average measured temperatures within and on the surfaces of the closure and cabling and the highest temperatures measured at those locations
4. The visual observation of the passage of smoke through the closure assembly.

Test Methods

The first series of fire tests, using gasoline, polystyrene foam, or polyethylene cables, were made in a two-story structure built to represent two vertically adjacent building bays in a telephone office. Each bay was 20' x 20' x 14', with the fuel load placed at the center of the lower chamber and the test assembly placed in the corner of the ceiling. The four walls of the fire chamber contained sets of louvers that could be preset to draw in air and emit combustion products, the resulting gaseous mixture of air and fuel determining the temperatures achieved and the duration of the fire tests. Fig. 1 is a photograph of this building

in use during a gasoline test. For a variety of experimental reasons, but principally because the fire-zone thermal behavior and the test-assembly measurements were judged as being too dependent on weather conditions, plus the considerable difficulty of scaling these sources up to reproducible two-hour fire endurance tests, later tests were made mostly in a small-scale indoor furnace and followed by several corroboratory tests in a large-scale furnace.

The furnaces will not be described in detail in this paper. The small-scale furnace was 6' x 6' x 6' externally, with its refractory brick interior being 4' x 4' x 4' and heated by two propane-fueled package burners. Concrete test slabs, 6' x 6', generally 8" thick, provided a variety of ceiling cable openings when the test assembly was mounted as in Fig. 2. This furnace has been found adequate to test fully cabled openings up to 1' x 2' in size, either in this mode or as horizontal penetrations in the furnace wall (Fig. 3). For larger penetrations the thermal mass of the cable bundle causes the furnace temperatures to lag undesirably below the desired values.

When the original building in Fig. 1 was enlarged and restructured to provide capabilities for conducting large-scale-growth fires in telephone equipment, it also included a large-scale furnace to test large openings or many small openings simultaneously, independently of weather conditions. This furnace, shown with the doors of the lower and upper chambers open (Fig. 4), has internal dimensions of 20' x 20' x 15', with four propane-fueled ribbon burners providing a test fire for a 12' x 15' concrete test slab containing a minimum of two closure assemblies per test. Photographs of two fully cabled assemblies are shown in Fig. 5. This is a lower-fire-chamber view of a full-length vertical cable bundle as found typically in wiring centers and a similar cable bundle truncated 18" below the ceiling level. Fig. 6 shows these cable bundles physically supported by being turned over cable ladders, the thermocouples on the bundles and a CCTV camera mounted on the wall behind. Tests have also been run on cabled closures with the cable suspended horizontally 18" below the ceiling to simulate cable runs mounted above equipment frames (see Fig. 7).

The results given in this paper have been taken from fire tests on a closure design called the 1' x 2' vertis closure. This consists of a metal frame around the ceiling side of the opening bolted to a 4" metal sheathing frame placed around the floor side of the opening. Both the ceiling and floor cover plates are cut neatly to size around the cable bundle, which is supported by cable ladders mounted above and below the closure. This arrangement is shown in Fig. 8 as it appeared prior to firestopping by 24-oz. mineral-wool bags tightly packed around the cable perimeter (Fig. 9). Finally, the floor plate is bolted down to the floor sheathing, and a high-temperature putty is pressed into place around the perimeter of the cable bundle to seal any gaps between the cable bundle and the metal plate.

Fig. 10 is a cutaway diagrammatic view of the test assembly typically dressed with a grid of thermocouple junctions designed to measure temperature gradients

developed during fire tests. The thermocouples were placed both within the core and around the perimeter of the cable bundle at eight levels up the length of the bundle, namely 12" and 6" below, at, and 4", 8", 12", 18", and 24" above the ceiling-plate level. Thermocouples were also emplaced within the mineral-wool insulation, on the metal floor cover plate and framing sheath, and on the concrete test slab upper surface. Bell System Practices require a 1' x 2' cable opening to incorporate a minimum of 3" of mineral-wool insulation around the front face and two sides of the cable bundle. A cable bundle of this cross-section — 9" x 18" — is termed a completely filled closure assembly. For many of the tests where experimental parameters were deliberately varied, a standard bundle, 4" x 12", termed a quarter-filled cable closure, was used. This quarter-filled condition simulates the majority of the cable-closure assemblies found in the field. All data were recorded on a data-acquisition system and the tests recorded in their entirety on videotape.

Experimental Results

Fig. 11 is a plot of the characteristic temperatures developed over the period of each test for four of the fire sources examined. Curve A shows that, for a 250-gallon gasoline fire, gas temperatures peaking at 1900°F were achieved within the firechamber at 20 minutes into the test (which flamed out at approximately 60 minutes). A 500-lb fire-retarded polystyrene foam stack, 8' x 8' x 4-1/2', gave even faster temperature rise behavior; as Curve B illustrates, gas temperatures ranging up to and over 2400°F (at which temperature several thermocouple failures occurred) were attained within five minutes at the center of the chamber, falling off within 18 minutes to flame-out. The data shown in Curve B for the decrease in temperature came from a thermocouple located in the corner of the chamber. The two furnaces had their propane burners set to track the temperature-time relationship of the ASTM E-119 furnace, which was reproduced within a 1-percent tolerance as measured by the area under Curve C. It was judged after this preliminary series of fire tests that only the furnace test conditions would provide an adequate degree of reproducibility and unambiguous data in the testing of cable closures. Such tests also paralleled the cable-penetration fire testing approaches being generated by IEEE 634 (now ANSI 634) and the proposed ASTM E-5 fire-testing method for cable penetrations.

It is of interest to compare the plots of energy fluxes during the time of test (Fig. 12). Curves A and B are the total energy fluxes experimentally measured by calorimetry in the large and small furnaces, respectively; Curves C and D are the corresponding radiant-energy fluxes experimentally determined by radiometry. These data show that the furnaces provide similar total energy fluxes as they track the E-119 temperature-time curve but that the small furnace has a significantly lower radiant energy component than the large furnace. This presumably reflects the difference in the furnaces' refractory linings as well as the burners' flame characteristics. Curves E and F are computed values for the energy absorbed by a 1' x 2' closure containing only mineral-wool bags in a small-furnace test and a 200-gallon

gasoline test, respectively. Note that the absorbed energy values in E are typically a factor of one-third of the impinging total energies. Furthermore, the computed values indicate that the closure assembly absorbs in the gasoline test twice as much energy at its peak temperature value as the small furnace and that it is about 30 minutes before Curves E and F indicate the closure has absorbed similar amounts of energy from each fire source. The gasoline test would appear to provide a greater thermal stress to a cable closure over the first half hour than does the E-119 furnace test.

The reproducibility of the thermal properties of the furnaces has been indicated in Figs. 11 and 12. Another comparison of reproducibility is given by the temperatures measured within a cableless vertis closure packed only with mineral-wool bags and given a 2-hour fire exposure test on the small furnace. Three tests were performed, and the measured temperatures are given in Table 1 for thermocouples placed at 2" intervals along two vertical planes through the closure, namely the central axis of the closure and at a distance of 6" from the concrete edge of the opening. These results indicate that the furnace testing of closures gives acceptable reproducibility.

With cabling present in the closure, at the quarter-fill capacity, three tests were run to establish the uniformity of temperature gradients from test to test. The results are summarized in Fig. 13 for the floor-plate level in terms of average measured values from thermocouples placed at the center plane of the bundle and from thermocouples placed at the perimeter of the cable bundle beneath the closure sealant (i.e., not on surfaces exposed to air). These results, plus those obtained in other tests, represent the typical spread in experimental measurements as found in both small and large furnace testing of cable bundles in closures. Point 4, calculated from the 60-minute cable perimeter data of one test, was well above the expected

variation in temperature spread, and its significance has not yet been resolved.

An example of the actual temperature gradients that develop across the horizontal section of the cable bundle (quarter cable fill) is shown in Fig. 14. The temperatures developed at the floor-plate level at discrete points on the cable-bundle perimeter and at the core of the cable bundle are given for the one-hour time (in parentheses) and for the two-hour time periods of a test in the small furnace. Peak temperatures of 307°F (1 hour) and 689°F (2 hours) occur within the center of the bundle. Temperatures on the cabling surfaces at the perimeter of the bundle average 185°F (1 hour) and 331°F (2 hours), with the highest measured values being 221°F (1 hour) and 558°F (2 hours). Temperatures measured on the surface of the surrounding closure metal floor plate were 126°F (1 hour) and 157°F (2 hours), respectively.

Fig. 15 shows the corresponding temperature gradients that developed along the central axis of a cable bundle (quarter cable fill) vertically from distances of 12" within the furnace fire zone to 12" above the closure floor plate of the test assembly. Within the furnace proper the average cable bundle core temperature is 1353°F (1 hour) and 1393°F (2 hours) as compared to average core temperatures of 298°F (1 hour) and 677°F (2 hours) at the floor-plate level. Within the actual closure itself, i.e., at 4" above the ceiling plate, the average temperatures measured were 531°F (1 hour) and 1047°F (2 hours), respectively.

The next experimental parameter examined was the effect of varying the pressure in the small furnace using a quarter-filled vertis cable closure as the test assembly standard. Table 2 lists the average values of temperatures measured at the floor-plate level within the center of the cable bundle and at the perimeter of the cabling *beneath* the sealant material. These values are given for elapsed time intervals of 1/2 hour, 1 hour, 1-1/2 hours, and 2 hours in each test. The tests were done with pressures of -0.02", +0.025", and +0.35" of water, respectively. The results show that, as the pressure is increased, the measured temperatures rise significantly at the 2-hour time period, although some inconsistencies appear in this apparent trend at the earlier time intervals.

In these furnace tests of the vertis closure there is no sealant material filling the interstices between cable strands in the cable bundle. Thus, under positive pressure test conditions, smoke emission from the closure assembly generally has been noted at about one minute into the test, reaching an apparent maximum emission at 15 to 20 minutes. For the next hour and a half of the test, the smoke emission was markedly less, until the last 20 to 30 minutes of the test, when the smoke emission began to increase once more. This characteristic smoke emission was noticeably affected by varying furnace pressures. With -0.02" water pressure no smoke passage was noted throughout the test, whereas, with +0.35" water pressure, the smoke emission was steady through the test.

With standard small-furnace test conditions established as a 2-hour temperature-time E-119 relationship, and with

Table 1. Distribution of Temperatures in Cableless Vertis Closure at 2 Hours

| Height (in.) Above Ceiling Plate | Temperature (°F) on Central Axis | | | Temperature (°F) at 6" Off-Axis | | |
|--|--|--------|--------|---------------------------------------|--------|--------|
| | Test 1 | Test 2 | Test 3 | Test 1 | Test 2 | Test 3 |
| 0 | 1630 | 1777 | 1772 | 1651 | 1731 | 1781 |
| 2 | 1131 | 1278 | 1568 | 1135 | 1271 | 1514 |
| 4 | 371 | — | 664 | 340 | 491 | 783 |
| 6 | 131 | 142 | 200 | 135 | 135 | 242 |
| 8 | 105 | 103 | 123 | 101 | 102 | 133 |
| 10 | 87 | 91 | 109 | 85 | 86 | 107 |
| 12 | 79 | 101 | 96 | 78 | 93 | 96 |

Table 2. Effect of Small-Furnace Pressure on Cable Temperatures*

| Pressure/Position | Average Temperatures | | | |
|---|----------------------|---------|--------------|----------|
| | 1/2 hr/°F | 1 hr/°F | 1-1/2 hrs/°F | 2 hrs/°F |
| Pressure -.020"H ₂ O | | | | |
| Center [†] | 126 | 335 | 506 | 665 |
| **Surface ^{††} | 128 | 238 | 296 | 369 |
| Pressure +.025"H ₂ O | | | | |
| Center [†] | 167 | 298 | 450 | 677 |
| **Surface ^{††} | 132 | 232 | 327 | 413 |
| Pressure +.350"H ₂ O | | | | |
| Center [†] | 242 | 338 | 747 | 955 |
| **Surface ^{††} | 138 | 222 | 347 | 532 |
| *Quarter-cable-fill bundles at floor-plate level. **Measured below sealant material. [†] Average of 3 thermocouples. ^{††} Average of 12 thermocouples. | | | | |

the furnace pressure at +0.025" water, a series of tests was run in which the cabled capacity of the vertis closure was increased from zero cabling to 100 percent of the permissible cabling for this 1' x 2' design. (As a comparison, 48 strands of 0.92" diameter switchboard cable would constitute a quarter-fill, and a 100 percent fill would contain 180 such cables.) The respective average temperatures developed at the floor-plate level at 2 hours for the core positions, for the perimeter cable surfaces just above the sealant, (that is, on the cabling surfaces exposed to air) and for the surrounding air are plotted in Fig. 16. As a comparison, the temperature of the metal floor plate at 2 hours is shown to be about 100°F for the cableless closure case. The plots indicate that the temperatures developed within the bundle pass through a maximum between the quarter-fill and half-fill closure capacity points but that the cable surface and air temperatures do not appear to do so. This phenomenon has also been noted in tests run on bundles of switchboard cable strands of other diameters and appears to be characteristic of the heat dissipation occurring within cable-bundle cores.

Whereas the effects of varying the pressure and the cable-opening fill with cabling have been presented for tests run in the small furnace, similar results were experienced in the large furnace. A further test parameter was explored in the large furnace by comparing the results from four tests on 1' x 2' closures filled by the 9" x 18" cable bundles, which were mounted in different configurations (see Figs. 5 and 7). In two of these configurations

the cable bundle was truncated 18" below the ceiling plate, with one of the truncated bundle assemblies mounted in a flat ceiling (similar to small-furnace test configurations) and the other between two 18" deep ceiling beams. The other two configurations used a cable bundle supported either vertically down a 15' run from ceiling to floor by a cable rack in one test, or with the same length of cabling bundle mounted on a cable rack suspended horizontally 18" below the ceiling prior to turning into the cable opening. These tests were designed mainly to determine whether the massive cable bundles would move during a 2-hour fire test and whether such movement would noticeably change the fire resistance of the closure assemblies.

The averages of the measured temperatures within the core of each bundle and on the surface above the sealant of each bundle are plotted as a function of time for the floor-plate level in each closure (Figs. 17 and 18). In practice, the ceiling-mounted horizontal rack broke loose from its position about 30 minutes into the test, with one end swinging to the floor of the furnace and the other end at the cable opening as its fulcrum. The cable bundle on the vertically mounted rack expanded and sagged during the test, but the rack support did not collapse until after the 2-hour test was finished. Thus, in both these tests a mechanical stress was induced on the cable closure in addition to the thermal stresses. Although variations in temperature gradients are noticeable in the first hour of testing, at the 2-hour time the average temperatures measured on the cable-bundle surfaces above the sealant are similar, indicating that the movements of the cables had no significant effects on the firestopping characteristics of the closure assembly.

On comparing the plots of the temperature data from the two cable assemblies mounted in a flat ceiling test slab with the data for the two assemblies mounted between beams, the curves appear similar up to the 90-minute point. That is, they are either almost linear or slightly sigmoidal in shape. It has not yet been resolved why the temperatures in both the cable cores in the flat ceiling assemblies rose rapidly in the final 30 minutes of the test. It is possible that the beam configuration provided more shielding of the tested closure assemblies from the convective energy component of the large-scale furnace.

Tests have also been run on a newer cable closure designed for floor penetrations of switchboard cable. In this closure, a modular type as opposed to the additive usage of the vertis closure, eight small groups of cables are held in individual cells within the 1' x 2' opening. Intumescent coated cards are used in place of mineral-wool bags as the firestopping medium within the concrete floor slab, and a high-temperature sealant is placed around each cable strand above the floor within a sheath. This cable penetration gives similar thermal gradients to the 1' x 2' cable bundle but allows no smoke to pass for the majority of the 2-hour duration of the fire test. The general details of the closure design are shown (Fig. 19).

Summary

A variety of fire tests have been run to assess the fire-resistance properties of cable penetrations. It has been determined that furnace tests, using the ASTM E-119 temperature-time dependence curve, are the most reproducible methods of those examined. Small and large furnaces have been characterized in terms of temperature and radiant and total energy fluxes. Experimental parameters, such as furnace pressure, area of cable hole filled with cabling, cabling rack mounting, and cable-hole structure, have been examined as to their possible effects on the temperatures developed in cable-bundle penetrations. Increasing the furnace pressure raises the temperature gradients within the closures, whereas increasing the cable fill produces maximal core temperatures with less than 50 percent of the available space filled by cables. Mechanical perturbation of the cable closure did not cause any

obvious changes in the thermal characteristics of the penetrations. Filling the interstices between cable strands in the bundle with intumescent material prevented the passage of smoke but did not reduce the temperatures developed.

A mathematical model has been developed to characterize the heat-transfer mechanisms within the cable-closure assembly. Attempts are being made to correlate the experimental results with the theoretical predictions, both for switchboard cabling and for power cabling. The fluctuations of data within tests and from test to test suggest that furnace tests using a few thermocouples emplaced by rote or by intuition may be misleading and that grids of thermocouples placed within and around cable bundles give more reliable information as to the thermal gradients developed during fire tests.



Figure 1. View of fire test building during 250-gallon gasoline fire

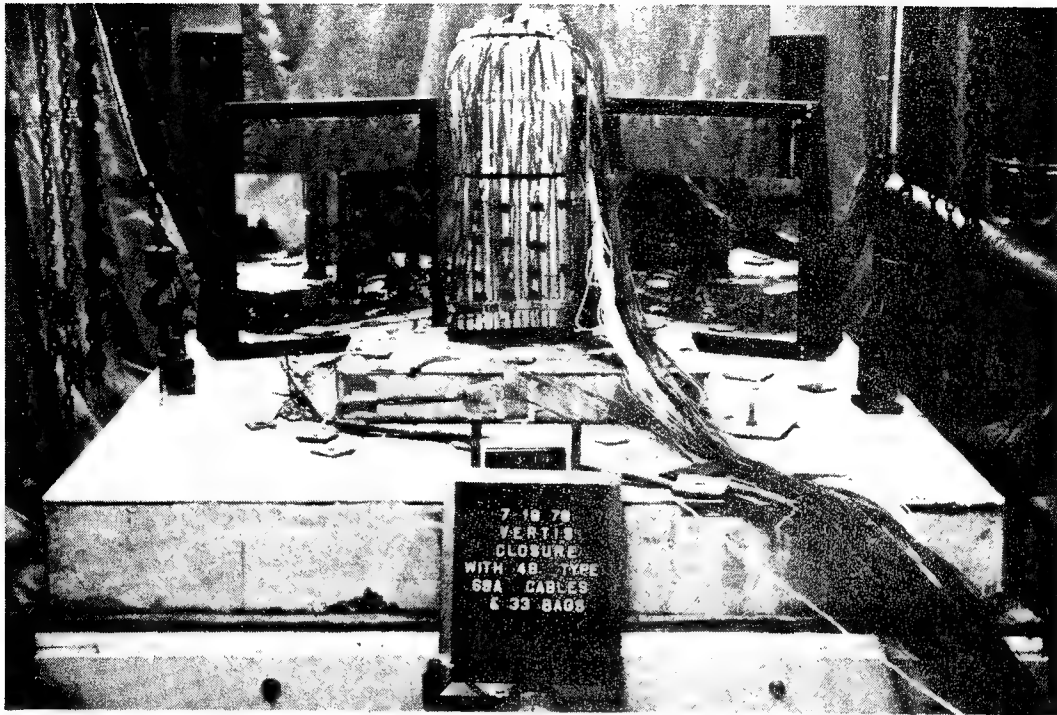


Figure 2. View of small-scale furnace testing vertical cable penetration

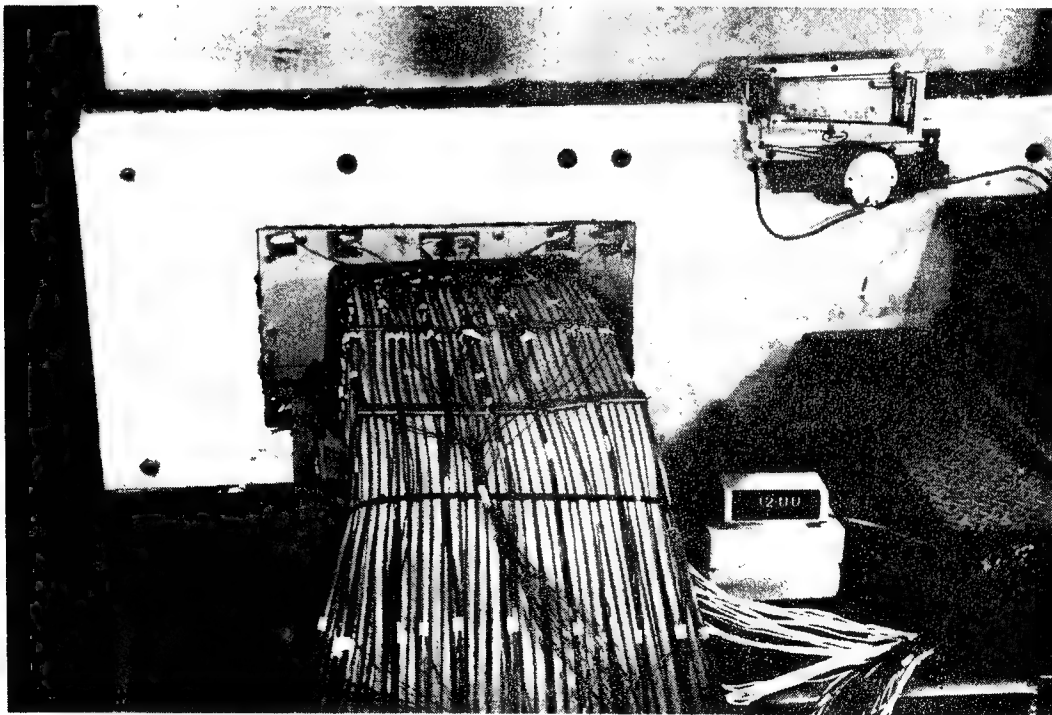


Figure 3. View of small-scale furnace testing wall cable penetration

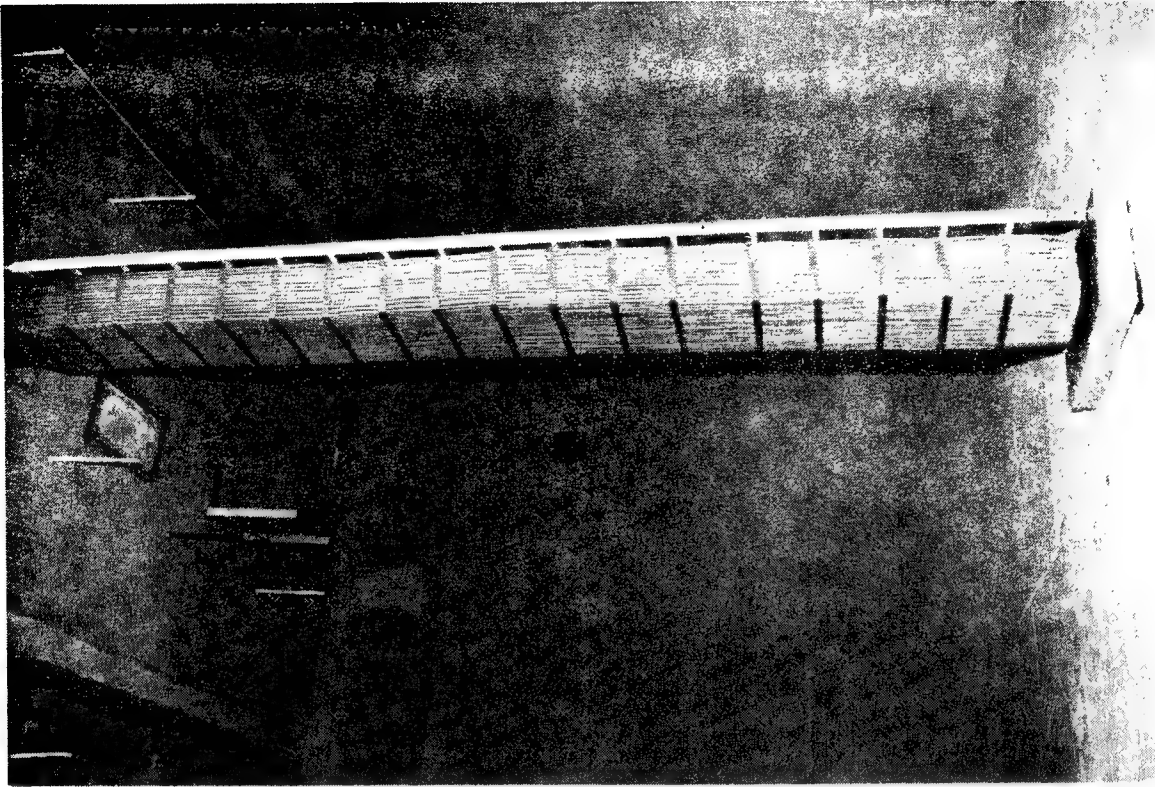


Figure 5. Fully cabled vertical cable bundle mounted in large-scale furnace fire chamber

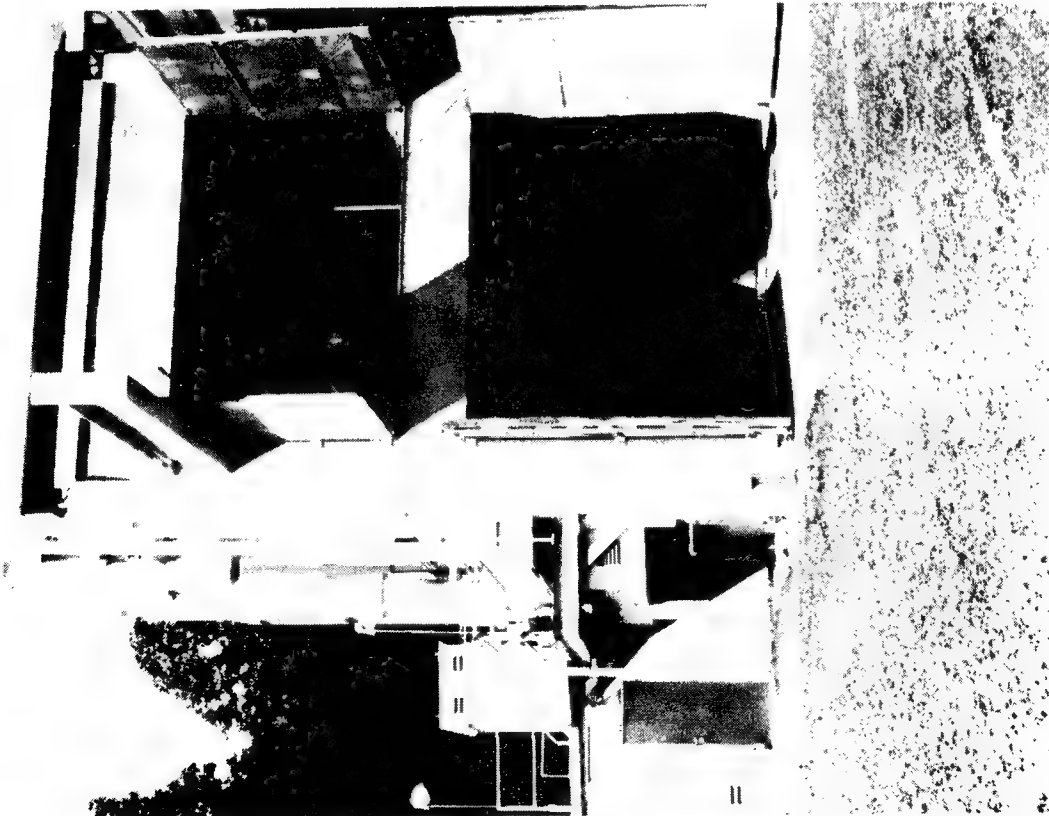


Figure 4. View of large-scale furnace with furnace doors open

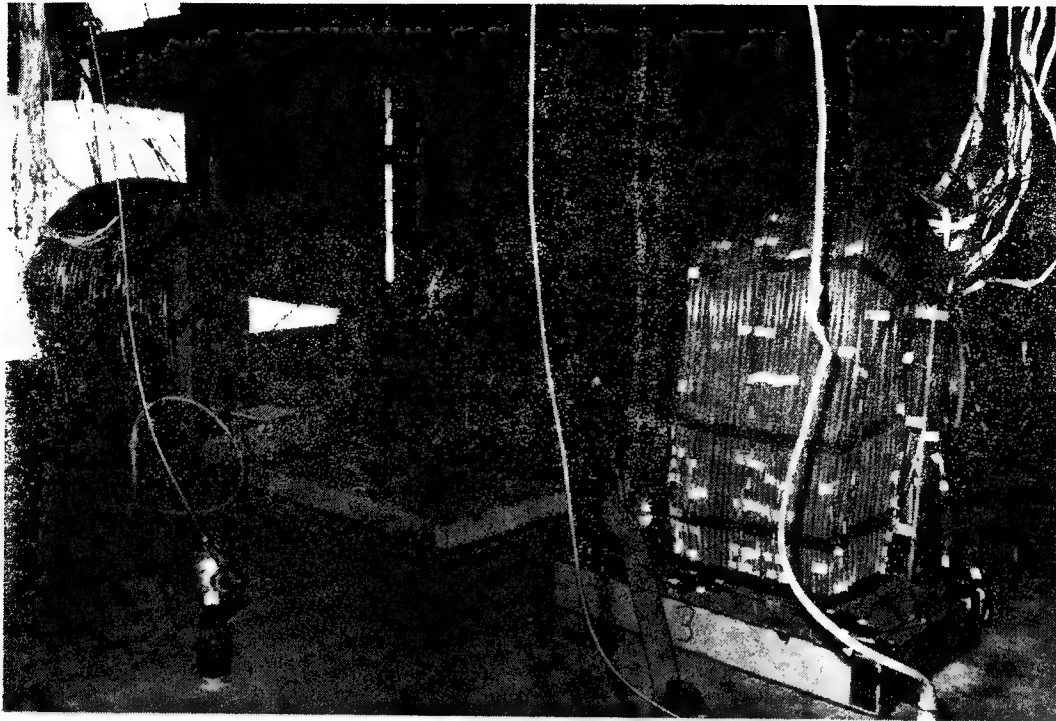


Figure 6. View of upper chamber of large-scale furnace with two fully cabled closures in place

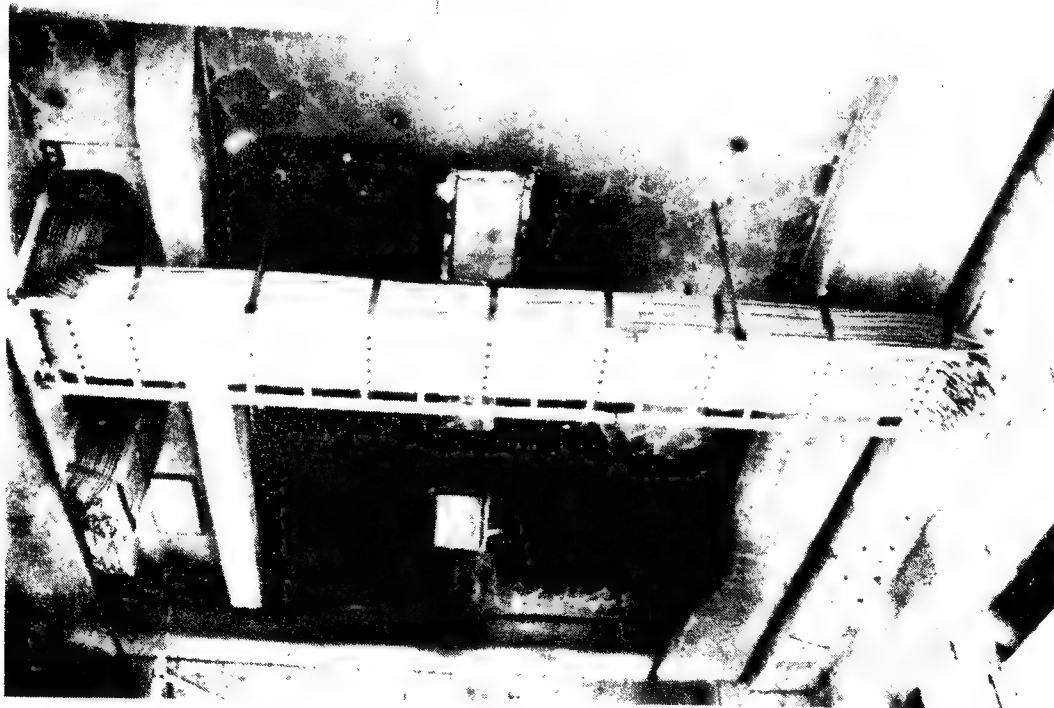


Figure 7. Fully cabled bundle suspended from ceiling of large-scale-furnace fire chamber

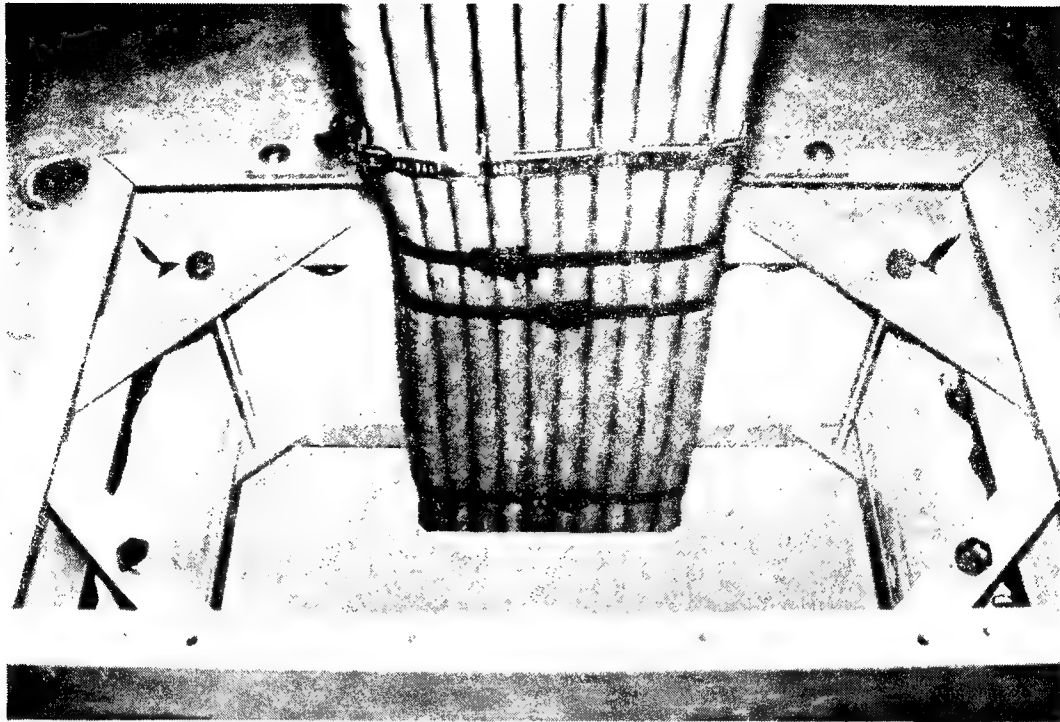


Figure 8. View of cable bundle in 1' x 2' vertis closure prior to firestopping



Figure 9. View of cable bundle in 1' x 2' vertis closure with mineral wool bags in place

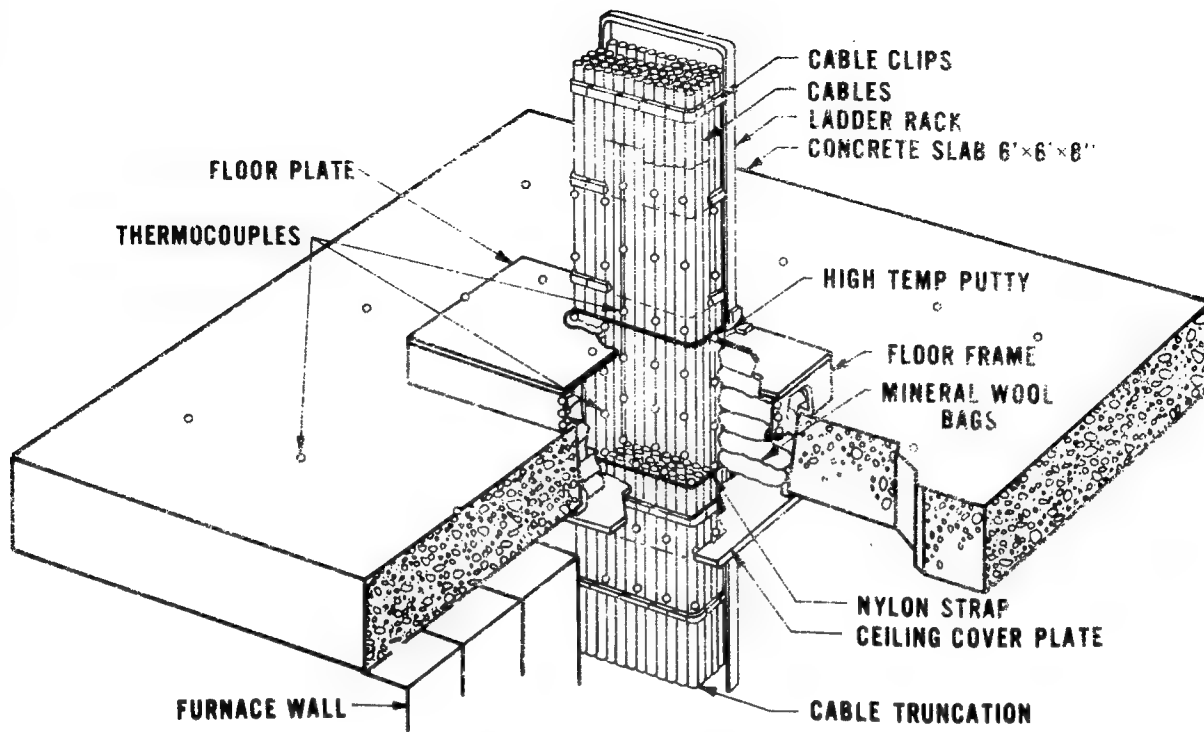
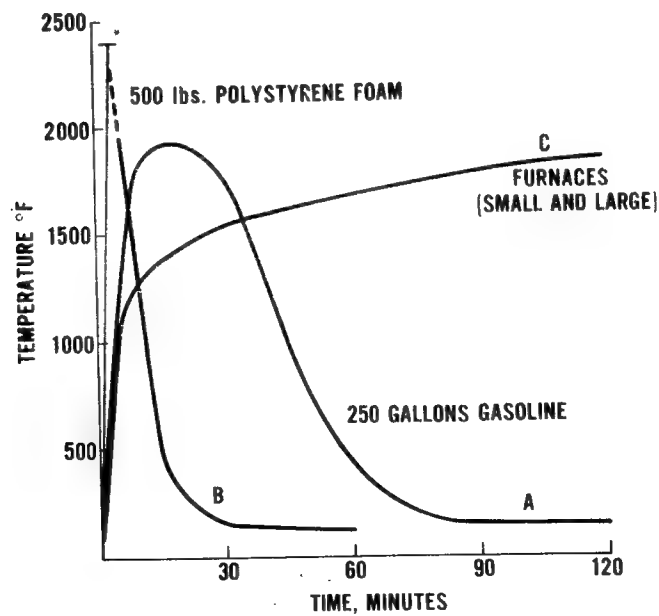


Figure 10. Cutaway diagrammatic view of vertis closure cable bundle showing thermocouple emplacement



• THERMOCOUPLE FAILURES

Figure 11. Characteristic temperature-time curves for fire test sources

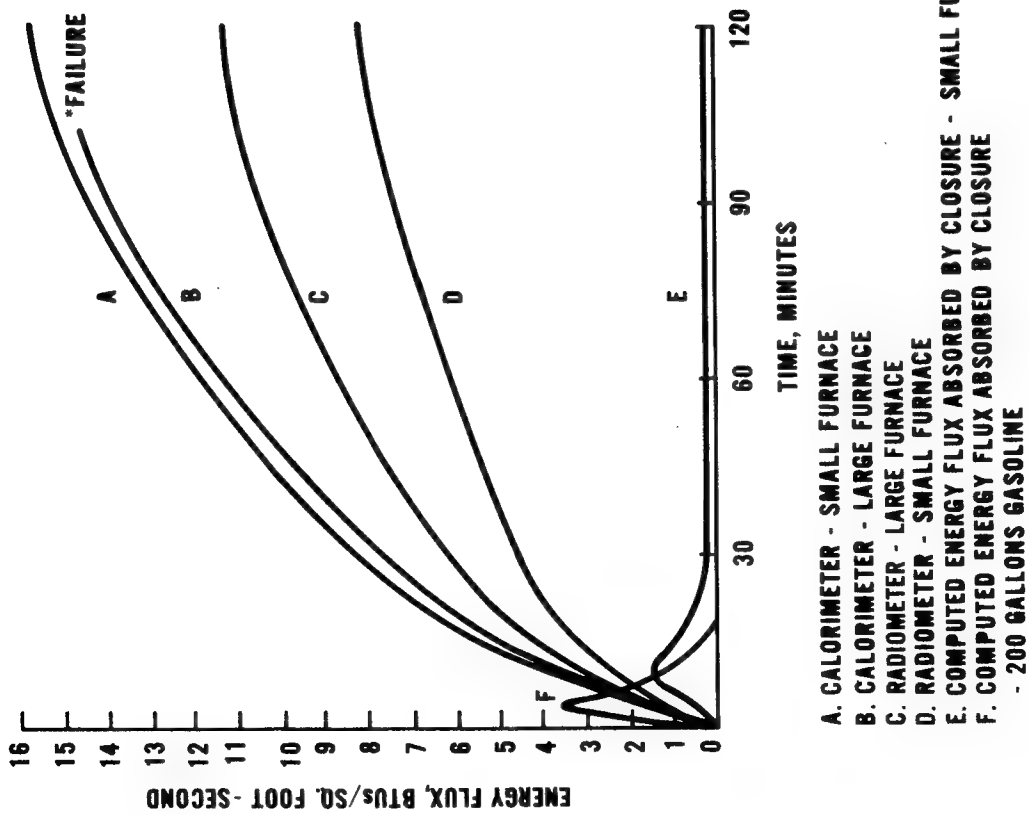


Figure 12. Energy flux dependence on time for three fire sources

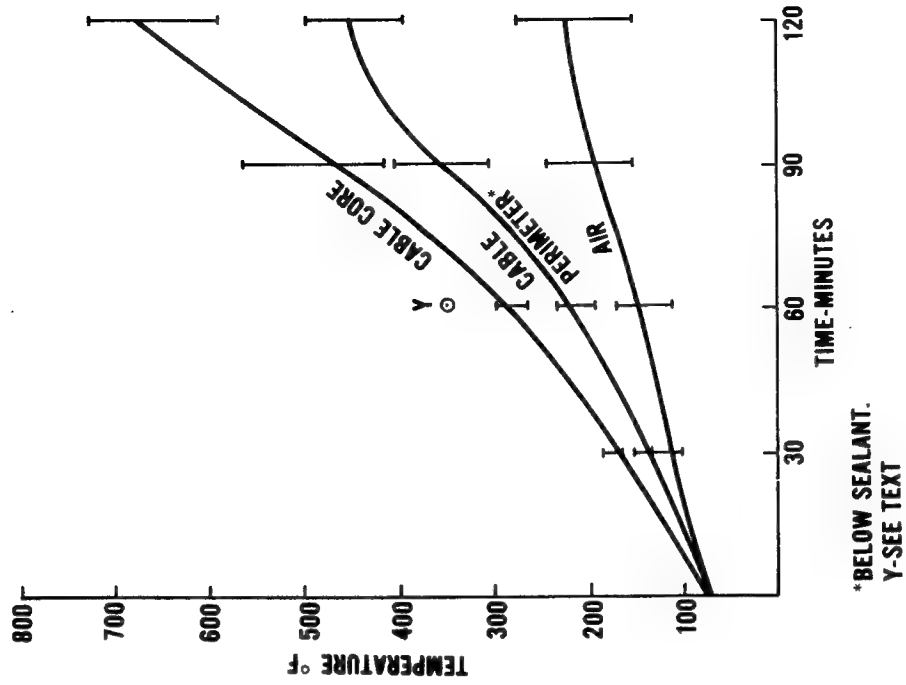
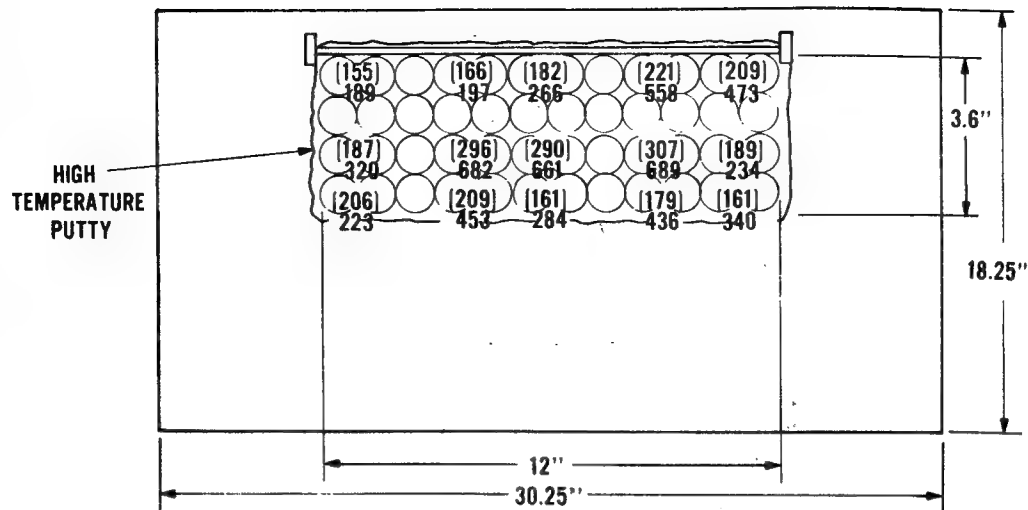
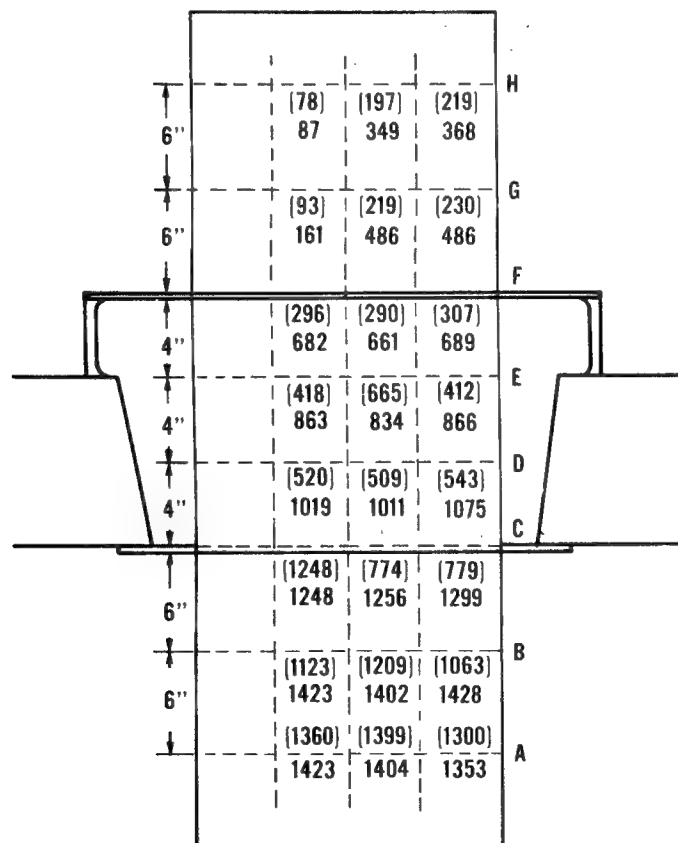


Figure 13. Calculated average temperatures in a quarter-fill cable closure at floor-plate level (average of three tests)



NOTE 1. (ONE HOUR) AND TWO HOUR TEMPERATURES IN DEGREES FAHRENHEIT

Figure 14. Temperatures measured at floor-plate level (quarter-fill closure, small furnace)



(ONE HOUR) AND TWO HOUR TEMPERATURES.

Figure 15. Distribution of temperatures* in vertical plane of cable-bundle core

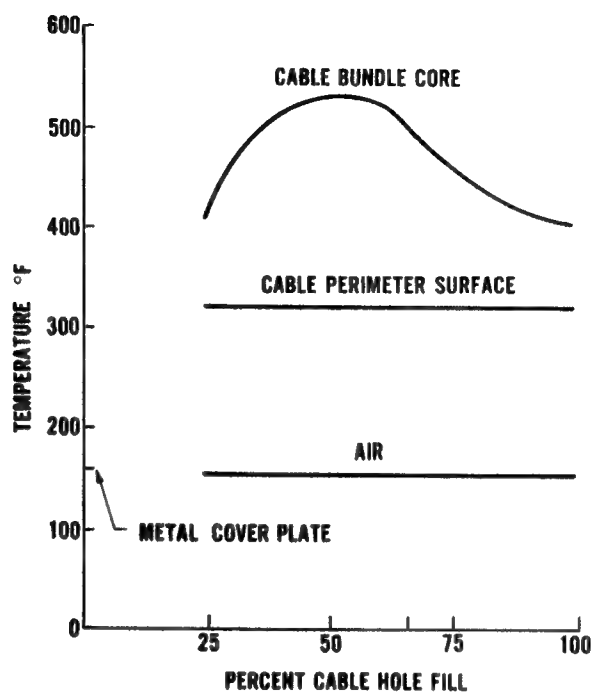


Figure 16. Temperatures measured at floor-plate level as cable-hole fill is increased (2-hour values)

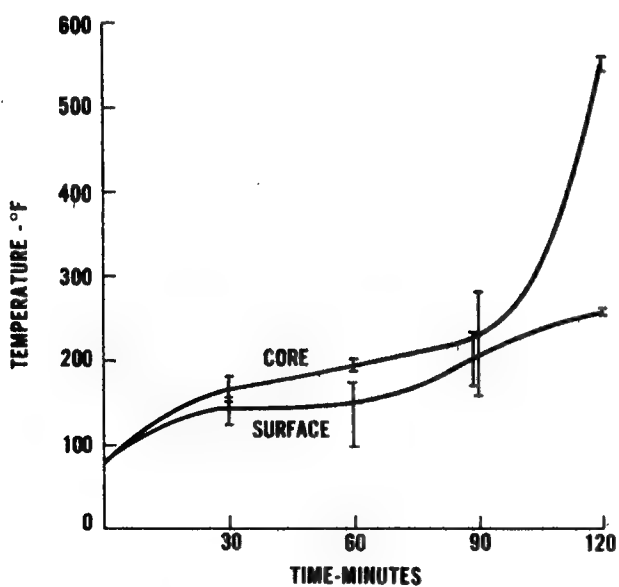


Figure 17. Temperatures developed with full cable bundles at floor-plate level (flat ceiling) versus time

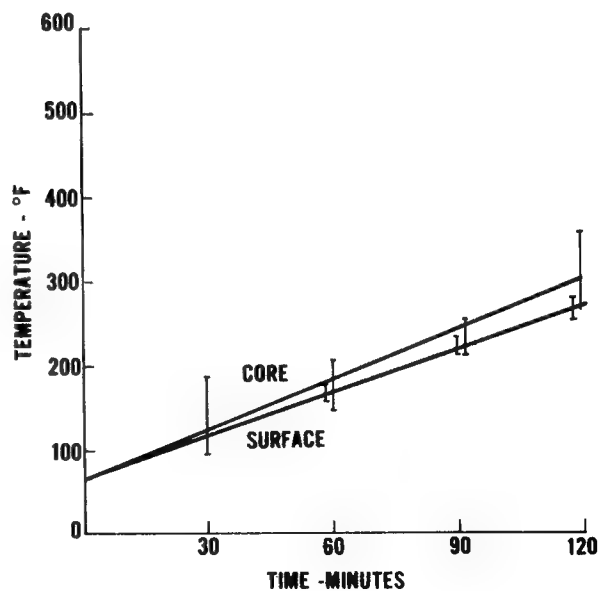


Figure 18. Temperatures developed with full cable bundle at floor-plate level (between beams) versus time

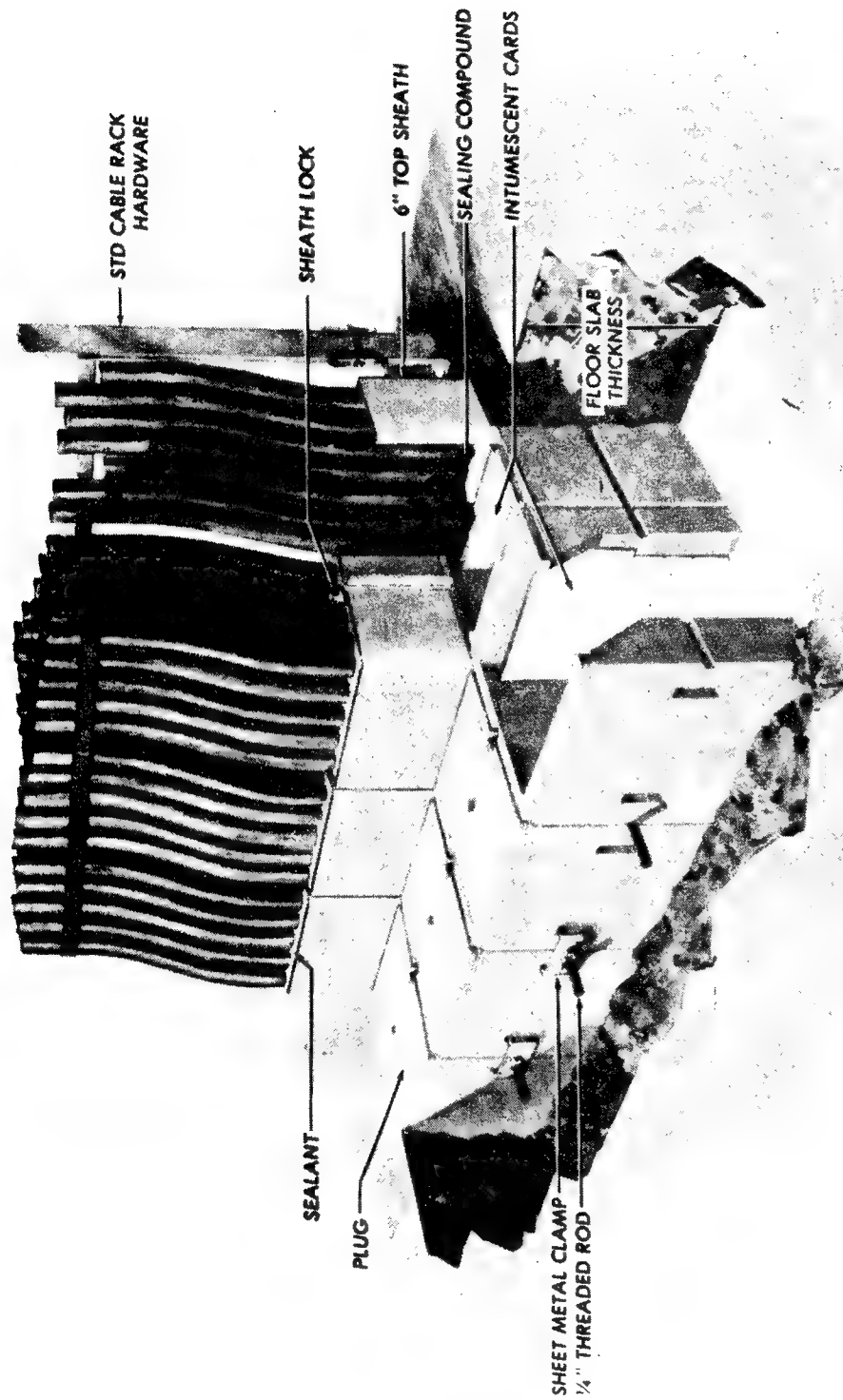


Figure 19. Variable modular floor penetration

MATHEMATICAL MODEL OF FLAME SPREAD THROUGH
GROUPED VERTICAL CABLES USING
RELEASE RATE DATA

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ABSTRACT

The possibility of using release rate data in conjunction with a mathematical modelling program to predict results of medium scale vertical flame tests for Grouped Cables has been investigated with encouraging results. The method is described.

Variations of the general test configuration have been accommodated by the model program and differences in operating procedure have been simulated by the program.

MEDIUM SCALE TESTS USED TO MEASURE FLAME SPREAD
THROUGH VERTICAL GROUPED CABLES

Several vertical cable test methods have been devised in North America and Europe which basically determine the same flame spread information. A list of some of these methods includes the following:

- | | | |
|----------------|------|---|
| Canada: | 1(a) | Ontario Hydro Provisional Specification to Determine Fire Retardancy of Insulated Power and Control Cable ¹ . (Figs. 1 & 2). |
| | 1(b) | Electrical and Electronics Manufacturers Association of Canada (EEMAC) Draft Spec. (similar to Ontario Hydro method). |
| U.S.A.: | 2. | IEEE 383 Vertical Test for Electric Cables ² . (Fig. 3). |
| Sweden: | 3. | Swedish Electrical Commission Test for Class F4 Cables ³ . (Fig. 4). |
| Norway: | 4. | A test similar to the Swedish standard. |
| Italy: | 5. | Standard CESI 20-22 Test ⁴ . (Fig. 5). |
| France: | 6. | Electricite de France Test |
| Great Britain: | 7. | AEI Cables Chimney Test ⁵ . |
| Great Britain: | 8. | BICC Vertical Test ⁶ . |

- Germany: 9. Kabel Metal Vertical Test⁷.
- Germany: 10. VDE Proposal DIN 57 472/VDE 0472, Part 804,
Test Method C.

Physical Variables of the Tests

Some tests are more definite than others in specifying the many variables possible which include the following:

- The presence or absence of an enclosure.
- Whether the test set-up is outside or inside a building.
- Whether a ladder or tray support system is used.
- How and to what extent the cables are attached to the support.
- The spacing between cable lengths.
- The number of cable lengths used for each test.
- The relationship between cable diameter and the number of lengths to be tested.
- The combustibles loading of the test.
- The presence or absence of an imposed air flow through the system or test facility.
- The actual air velocity through the chamber during the test.
- The ignition fuel source - usually a gas burner or an open flaming liquid tray.
- The temperature and the heat output rate of the igniting source.
- The position of cable flame impingement of the igniting source.
- The orientation of the igniting source.
- Results recorded during the test:
 - Flame Spread, Extent and Rate
 - Smoke evolved
 - Toxic and corrosive gases

Some of these vertical test facilities are fairly complex and are unique in one or more features, but they are designed with the same basic principles. These tests would include the Italian,

French, British, German, and some American tests, whereas the Swedish, American IEEE, and Canadian Ontario Hydro tests have been more frequently duplicated.

Enclosures

Tests which are conducted within an enclosure are in the vast majority, if only to control products of combustion and to make the test manageable. Most test enclosures are an enclosed square or rectangle, but some are open on one side. Some enclosures could be described as a small room. The IEEE method which is carried out indoors specifies no room size.

Ignition Source

The ignition source is a second important factor in comparing methods. The most common source is a gas burner, but many gas input rates have been used. Other ignition sources³ have been used, the main one being ethyl alcohol (Fig. 6). Two methods^{4,6} reviewed used radiant electric heating element bars.

Ventilation and Air Flow Rate

Since the presence of adequate oxygen is necessary to supply a fire situation, the presence or absence of a forced, or a least adequate convective air supply is required. Many specifications have no particular requirement but the IEEE test recommends an air change in two minutes. The draft EEMAC method specifies a linear air flow of 1 metre per second at burner level. A major contributing factor to the air change rate is the size of the enclosure air entrance and exit openings. These vary widely with the different test set-ups and may be a factor contributing to variability experienced in a recent round robin study conducted on cable using the draft EEMAC test method. The test specification requires a minimum exhaust opening of 0.36 m². Individual test facilities openings varied from 0.36 m² to 0.93 m².

Cable Support Systems (Fig. 7)

Cables subjected to vertical tests are normally supported and held in position by a device which can be a type of ladder or a commercial type cable rack or tray. Generally speaking, the more enclosed the tray, the more severe the fire exposure intensity, due to lower heat radiation to the surroundings (emissivity) and less cool air mixing (entrainment), assuming the incident heat flux is applied from the open side. The ladder specifications are usually detailed in the test method, as well as the type and extent of attachment of the cables to the ladder or rack. The Italian and BICC methods use both sides of the ladder for support of the cable and both sides are subjected to the heat flux from the ignition source.

Cable Spacing and Cable Loading

One of two general methods of specifying how many cables and what degree of spacing between cables is used for most tests. Many specifications on the number and spacing of cables to be tested are dependent on the physical diameter of the cable. This method has been widely used in North America. The European approach has generally been to load the test rack to a specific weight of combustibles per metre of vertical run, usually 5 or 10 kg/m, with a minimum number of cable lengths to be used sometimes given. European tests have been usually conducted with the cable lengths placed as closely together as possible, but some recent tests have been run with spaces between lengths.

MATHEMATICAL MODELLING OF A VERTICAL GROUPED CABLE TEST

The mathematical model of flame spread through vertical grouped cables was originally written to model the Ontario Hydro vertical grouped cable test, using release rate data generated from tests using the Ohio State University release rate apparatus (Fig. 8). The model was intended to predict vertical flame spread through vertically oriented cable and is sufficiently flexible to incorporate variables encountered in different tests, whether caused by the influence of test enclosure shape and size, air flow, ignition source type and size, or rack and cable sizes, spacing and configuration.

The basic mathematical relationships used to describe vertical flame travel are mass, momentum, and energy balances on a series of incremental volumes (horizontal "slices") of the plume fronting the grouped cable. Figure 9 illustrates the configuration and flows into and out of the incremental volumes.

The model uses the empirically derived release rate data as input to the mass and energy balances. To relate mass loss rate to heat release rate, a value for the heat of combustion of the decomposition gases is needed. Since mass flow rate of decomposition gases is small compared to that of the plume, the error introduced by an inaccurate heat of combustion value is small compared to the error introduced by estimating heat release rates from mass loss rates since the heat release is the most important part of the energy balance.

The major assumptions made in deriving the model are: 1) the vertical velocity, gas concentration, and temperature within the plume are uniform at the same height, i.e. over a horizontal plane, 2) the width of the plume is equal to the width of the cable rack, and 3) the smoke concentration is such that the plume acts as a grey body having a emissivity of 0.7.

Referring to Figure 9, the overall mass balance is made in terms of the mass leaving the upper surface of the incremental volume minus that entering the lower surface. The difference is equal

to the mass entering the incremental volume on the cable side as decomposition products, and on the plume boundary as entrained air, or:

Mass Balance: Out-in = Entrainment + Decomposition Products

$$\dot{m}_o - \dot{m}_i = \rho_o u_o A_o - \rho_i u_i A_i = E (\rho/\rho_a)^{\frac{1}{2}} \rho_a u (y+2x) dZ + r_h y dZ / H_v$$

where:

| | |
|----------------------------|---|
| \dot{m} = mass flow rate | dZ = Incremental height |
| ρ = density | r_h = rate of heat release |
| u = velocity | H_v = net heating value of decomposition products |
| A = Area | |
| E = Entrainment Coef. | Sub. a = ambient conditions |
| x = Plume depth | " o = out |
| y = Plume width | " i = in |

In a similar manner an energy balance can be written by setting the difference in sensible heat of gases leaving and entering the upper and lower surfaces equal to the losses by radiation and convection to the cable and surroundings plus heat added by the decomposition products:

Energy Balance:

Out - In = Heat Generated - Heat Loss by Radiation

- Heat Loss by Convection + Heat in Decomp. Products

Reference Temperature = Ambient Temperature = T_a

$$(\Delta H_o - \Delta H_i) / dt = \dot{m}_o c_{pm} (T_o - T_a) - \dot{m}_i c_{pm} (T_i - T_a) =$$

(For Oxygen limiting:)

$$= \dot{m}_{ox} Q_{ox} - [\epsilon F_{PS} \sigma (T_p^4 - T_a^4) + \epsilon F_{PW} \sigma (T_p^4 - T_w^4) + h (T_p - T_w) - r_h c_{pd} (T_d - T_a) / H_v] y dZ$$

(For Fuel Limiting, i.e. excess oxygen)

$$= r_h y dZ - [\text{same as in bracket above}] y dZ$$

where:

| | |
|---|---|
| dt = time increment | F_{PS} = view factor, plume to surroundings |
| \dot{m}_{ox} = mass rate O_2 into dV | F_{PW} = view factor, plume to wall |
| c_{pm} = mean c_p of plume | h = combined convective and radiative heat transfer coefficient |
| Q_{ox} = heat released/mass oxygen consumed | T_w = temp. of wall |
| ϵ = emissivity of plume | T_d = decomposition temperature of wall material |
| σ = S. Boltzmann Const. | T_p = ave. plume temperature |
| c_{pd} = heat capacity of decomp. products | |

Force Balance

A force balance on the incremental volume can be made by equating the change in momentum entering and leaving to the buoyance and frictional forces on the volume:

$$\dot{m}_o u_o - \dot{m}_i u_i = xyg(\rho_a \rho) dZ - f_f \rho u^2 dZ/2$$

where:

f_f = average value of friction factor over dZ

g = acceleration due to gravity

An oxygen and fuel balance is made for each incremental volume in order to determine if fuel or oxygen is limiting. "Fuel" is expressed in terms of the experimentally determined rate of heat release. If sufficient oxygen is not available to react with all the fuel, the unburned "fuel" passes to the next volume increment until sufficient oxygen is entrained to react and produce the available rate of heat release.

Oxygen Balance:

$$(\dot{m}_{ox})_o - (\dot{m}_{ox})_i = 0.23[E(\rho/\rho_a)^{\frac{1}{2}}\rho_a u]y dZ - (r_h y dZ + \dot{f}_i)/Q_{ox}$$

where:

\dot{f}_i = "potential" rate of heat release in unburned combustible gases entering.

$(\dot{m}_{ox})_o$ cannot be less than 0.

Unburned Fuel Balance (in terms of "potential" heat release):

$$\dot{f}_o - \dot{f}_i = r_h y dZ - Q_{ox} \dot{m}_{ox}$$

If: $r_h y dZ + \dot{f}_i > Q_{ox} \dot{m}_{ox}$, O_2 is limiting

If: $r_h y dZ + \dot{f}_i < Q_{ox} \dot{m}_{ox}$, Fuel is limiting (excess O_2)

Flux-Time Product:

To determine when an incremental area ($y dZ$) of cable starts to burn, the Flux-Time Product (FTP) for that area is calculated and compared to the minimum Flux Time Product (FTP)_{min}. When FTP_{min} is exceeded, the surface will release heat, i.e. start to burn. The FTP of a material or product is calculated:

$$FTP = \sum (\text{Flux}_i - \text{SPF})^n \Delta t_i$$

where:

- Flux_i = Average incident flux over time increment "i"
- SPF = Self Propagating Flux; that flux at which a flame will just propagate from a point of flame impingement.
- Δt_i = time span of increment "i"
- n = empirical constant; for many materials, "n" = 1; for fire-retarded materials, "n" may be greater than 1.

At some level of FTP the sample will start to "burn", i.e. has a significant Rate of Heat Release as shown by Figure 10. The product of the excess flux (Flux - SPF) times the "burn" time is the Minimum Flux-Time Product for that heat flux. Calculation of the Minimum Flux-Time Product (FTP_{min}) is shown by Figure 10. The plywood has a Self-Propagating Flux = 0.75 W/cm².

For Plywood:

$$FTP_{min} = (3.0 - 0.75) \cdot 25 = (1.5 - 0.75) \cdot 75 = 56 \text{ W, s/cm}^2$$

To solve the time dependent set of equations, a trial and error procedure is used. At time "t" the change in \dot{m} , u, \dot{f} , T, etc. across each incremental height is found from the average conditions existing in each incremental volume. Initial values for \dot{m} , u, \dot{f} , T, etc. entering the base of the first incremental volume are determined by the ignition source.

The output from the upper surface of a volume increment is the input to the lower surface of the next increment.

Temperature change of the cable for each incremental area is calculated from the heat absorbed by the cable during the time increment, Δt , and the weight and heat capacity of the cable.

Heat flux to the cable is calculated from the plume temperature, and the total heat released from each incremental area of the cable during preceding time increments is stored. Thus the rate of heat release can be calculated from the subroutines giving Heat Release Rate vs. Total Heat Release as a function of incident flux (see Figure 11).

After all incremental volumes are calculated at time "t", the operation is repeated at time "t + Δt " until total run time desired is reached.

The computer program used for all modelling to date uses data which assumes:

1. a test enclosure which does not restrict air flow;
2. a flow of air past the cable lengths which is influenced only by natural convection;
3. a gas flame heat source imposed on one side of the cable lengths;
4. cable lengths spaced to simulate the actual configuration in the test modelled.

ADAPTABILITY OF THE CABLE MODEL

To model a test not conforming to these restrictions three avenues of adaptation can be used.

1. One involves changes to the computer program and would only be used where a very different imposed condition is used for the test. An example of this might involve a narrow vertical chimney with forced air flow.
2. The second means of adaptation is the facility to modify a subroutine, which is then linked with the main program, in which is written the required information characteristic of the particular cable and loading situation of the test to be modelled. This is done as a matter of course since all cables are characterized by different flammability response characteristic equations. In this subroutine can be placed factors to compensate for discrepancies between the configuration of the cable used in the release rate test and that in the test to be modelled.

3. The third means of adaptation is the adjustment of the "constants" for the test being modelled. These include important factors such as maximum total heat release, the minimum flux-time product, self-propagating flux, flame temperature, velocity of the fuel jet impinging on the cable, emissivity of the flame plume, entrainment coefficient, and several other factors, some of which would be constant for a certain test to be modelled but which probably would be changed for a different test to accommodate different physical conditions.

A TYPICAL MODELLING PROCEDURE USING RELEASE RATE DATA

As an example to illustrate the mechanics of the modelling routine, we chose a power control cable containing no internal shield to complicate release rate results. The cable burned in a reasonably predictable manner, showing only slight initial surface burning accentuation in heat release, thereafter rising to a maximum, then quite rapidly declining in heat release rate. Rate of rise of heat release increased directly with heat flux, as would be expected. However, an incident heat flux higher than 30 kW/m^2 did not appreciably change the maximum rate of release but shortened the burning time.

The cable lengths were positioned for release rate tests in a configuration resembling the actual IEEE 383 test (Figure 11), i.e. three lengths of cable spaced at one-half the cable diameter between them. Release rate tests were conducted at 60, 40, 30, 20, and 15 kW/m^2 . From these data, an estimated value of 12.5 kW/m^2 was obtained for the self-propagating flux. Heat Release Rate vs. Total Heat curves were plotted (Figure 12) for each heat flux and an appropriate envelope curve approximating the overall shape of the curves was drawn.

Sufficient points were taken on this curve to develop the best equation to fit the curve, the initial point taken being the projection of the curve envelope back to intersect the release rate axis. This point represents an approximation of the heat release rate if the entire exposed surface of the specimen was ignited simultaneously. Four other points were taken, one at the maximum release rate peak of the curve envelope, a second at the approximate total heat release point, and at two other intermediate points.

Since maximum release rate at low incident heat flux varies directly with heat flux, some variable must be introduced to relate maximum release rate to incident heat flux. The relationship for this cable was found to be the following.

TABLE #1

| INCIDENT HEAT FLUX - kW/m ² | MAXIMUM HEAT RELEASE RATE - kW/m ² | |
|--|---|---|
| | <u>1</u> VALUES FROM RELEASE RATE RESULTS | <u>2</u> MATHEMATICAL APPROXIMATION |
| 60 | 85 | 85 |
| 40 | 88 | 85 |
| 30 | 85 | 85 |
| 20 | 65 | 64 |
| 15 | 55 | 53 |

A simple subroutine to enter this relationship and the curve equation was then written. In the subroutine, maximum heat flux was limited to 30 kW/m², then 30 kW/m² and lower heat flux levels were accommodated by the following statement:

Rate of Heat Release = Max. Rate of Heat Release x (Flux 30+10)/40.

Substitution of heat flux levels of 30 kW/m² and lower in this equation gave the relationship shown in Col. 2 of Table No. 1, a good approximation to the values determined experimentally. A statement is usually included to "zero" rate of release values should they occur as negative values at any time. The subroutine was compiled and then linked to the main model program.

During the actual modelling run values were entered for the decomposition temperature of the cable, the effective flame temperature, the net heating value of pyrolysis gases, the weight of cable per unit area, the time-flux minimum for self-propagation, the heat capacity of the cable, the self-propagating flux, the length of height increment, entrainment coefficient, run time, time increment, maximum total heat release, emissivity of the flame plume, and velocity of the plume impinging on the cable lengths.

MODELLING TEST RESULTS

The results printed are in tabular form giving updated information for the end of discrete time intervals. An interval of 60 seconds and a cable length increment of 0.2 m (0.5 ft.) are usually adequate to provide sufficient resolution to determine:

1. a predicted time of test failure, i.e. flame reaching a certain height above the ignition source, specified by the test requirements;
2. a maximum height extent of flaming involvement of the cable (below or above the test requirements);

3. the time to total flaming involvement of the cable lengths, i.e. when the cable is involved to the top of the test rack or tray.

Results using this modelling routine for the control cable tested indicated the following:

TABLE #2

| | TIME TO BURN TO 2 m (6 ft.) HEIGHT (IEEE FAILURE) | TIME TO BURN TO 3 m (10 ft.) HEIGHT (TOP OF ONTARIO HYDRO TEST) |
|---|---|--|
| Modelled at Ohio State University using release rate data generated at O.S.U. | 11 minutes | 17 minutes |
| Modelled at Northern Telecom using release rate data generated at N.T. | 10 minutes | 14 minutes |
| Actual IEEE test result | 14 minutes | |

MODELLING OF A VERTICAL CABLE ROUND ROBIN TEST

A round robin test was conducted in Canada on five cables using the draft EEMAC vertical grouped cable test by five testing facilities equipped with similar, but not identical, equipment. The cables were also studied using the release rate apparatus and the modelling procedure. The cables were tested for release rate data at Northern Telecom and the modelling prediction was carried out at Ohio State University. Test results and the model predictions are shown in Table No. 3.

TABLE #3

ROUND ROBIN 1979 - RANGE OF TEST RESULTS
LENGTH OF CHAR (m) - TRIPLICATE TESTS

| CABLE TESTED | TESTING FACILITY | | | | | TOTAL RANGE | MODEL PREDICTION |
|--|------------------|---------|---------|---------|------------|-------------|---------------------|
| | A | B | C | D | E | | |
| Unscreened Communication Cable 24 AWG/ 25 pr. with PVC Jacket. | -- | 0.5-0.7 | 0.5-0.7 | 0.7-0.8 | 0.6 (±.04) | 0.5-0.8 | 0.6 at 240-300 sec. |
| Teck 14 AWG/3 with PVC Jacket. | 0.5-1.0 | 0.4-0.7 | 0.6-0.8 | 0.7-1.0 | 0.3-0.6 | 0.3-1.0 | 0.9 at 240-300 sec. |
| Teck 12 AWG/3 with PVC Jacket. | 0.8-1.0 | 0.3-1.0 | 0.4-0.6 | 0.9-1.1 | 0.4-0.5 | 0.4-1.1 | 1.1 at 240-300 sec. |
| Screened Communication Cable 22 AWG/ 18 pr. with PVC Jacket. | 0.9-3.0 | 0.8-1.0 | 1.4-1.6 | 0.9-2.4 | 0.9-1.2 | 0.8-2.4 | 0.9 at 240-300 sec. |
| TWU 2 AWG with PVC insulation. | 0.9-1.4 | 0.8-3.0 | 1.4-1.8 | 1.3-2.3 | 1.5-3.0 | 0.8-3.0 | 0.8 at 360 sec. |

Failure is evidence of char in excess of 1.2 m.
 A value of 3.0 indicates the cable group burned to the top of the rack.

A study of the results obtained from the actual tests indicated that testing lab E had the smallest deviation from the average. This can probably be attributed to the fact that it was the only facility which was indoors, isolated from outdoor weather and temperature variations. Testing labs A, D and E generally rated cables worse than labs B and C, but no single variation in the test facilities could be found to which this fact could be attributed.

Comparing the model predictions to the actual test results, it was found that in all cases the predicted value was within the total range of the testing lab results. The first three cables in Table No. 3 were expected to pass the test, which they did. The model predictions indicated that they would pass, and ranked them in the same order as the actual test results range indicated. Data from the other two cables were more variable than the actual test results and the model prediction in both cases was at or near the bottom of the range of the tests. Modelling results were, however, within the range of actual tests even in these cases.

The inference to be drawn from this is that, as a first attempt to model vertical flame spread in grouped cables, the technique is capable of a reasonably close prediction of an actual test, and that it can be a useful tool in evaluating the flammability performance of cables.

ADVANTAGES OF THE USE OF RELEASE RATE DATA MODELLING

All laboratories running release rate tests using the Ohio State apparatus determine release rates for heat and smoke. However, increasingly more facilities are adding apparatus to analyze for other products of combustion, e.g. carbon monoxide, hydrogen cyanide, nitrogen oxides, and others, including monitoring the depletion of oxygen during release rate runs. Using similar techniques, release rate data for these products of combustion can be used to model rates of release and total concentrations during cable fire test situations, or, given enough specific detail of real cable fire situations, they can be used to predict the surrounding combustion products concentrations. Continuing work is in progress⁸ to include these products in a mathematical predictive model.

Large scale cable tests and real fires involving cable are difficult or impossible to analyze for smoke and toxic gas release but modeling techniques using release rate test results provide the means necessary to calculate concentration information to be used in assessing possible cable fire situations.

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4. Italian Standard CEI 20-22 - Cavi non propaganti l'incendio.
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8. ASTM Subcommittee E5.16 on Appliances and Equipment.

Edwin E. Smith was born in Sugarcreek, Ohio, and received his academic degrees in chemical engineering at the Ohio State University; his Ph.D in 1949. Major fields of interest include flammability research and industrial pollution control. He is a member of the American Institute of Chemical Engineers, American Chemical Society, National Fire Protection Association and ASTM.

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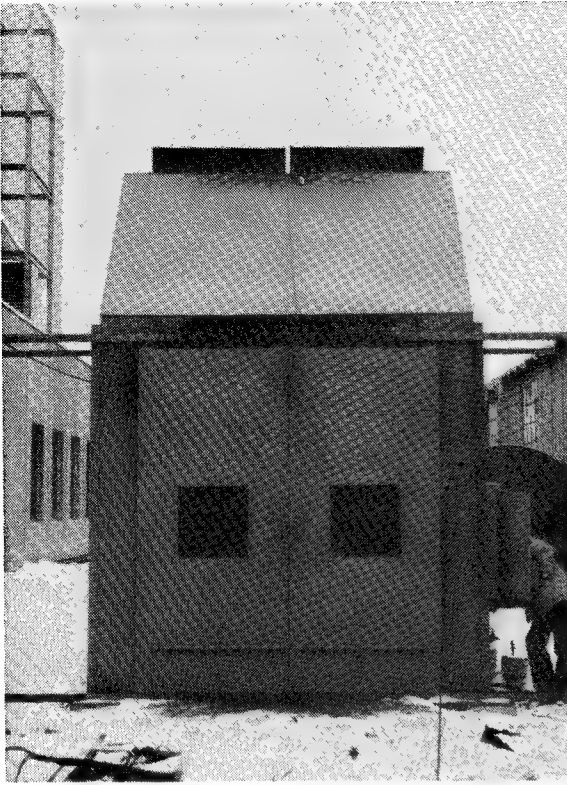


FIG. 1 ENCLOSURE FOR ONTARIO HYDRO TEST



FIG. 2 START OF O-H VERTICAL GROUPED CABLE TEST

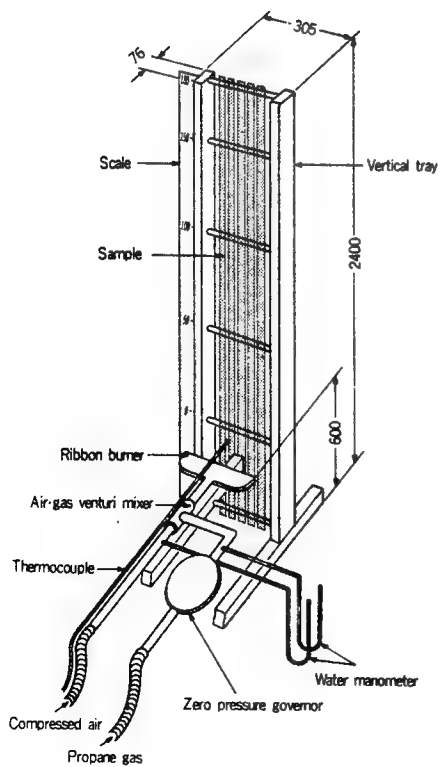


FIG. 3 EQUIPMENT OF IEEE TEST

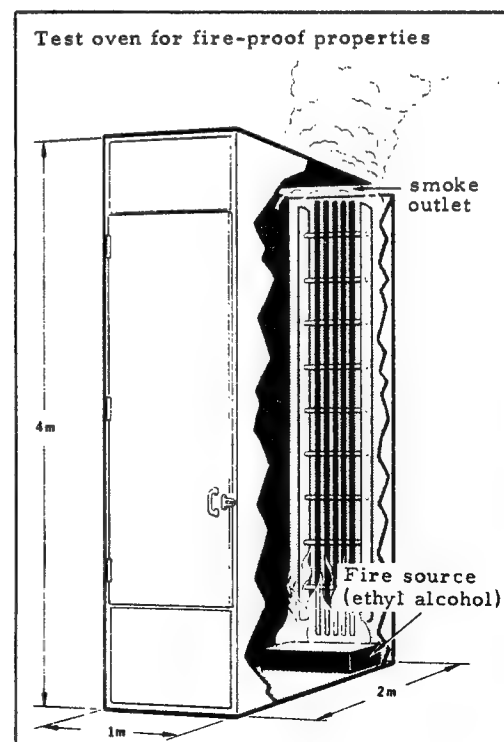
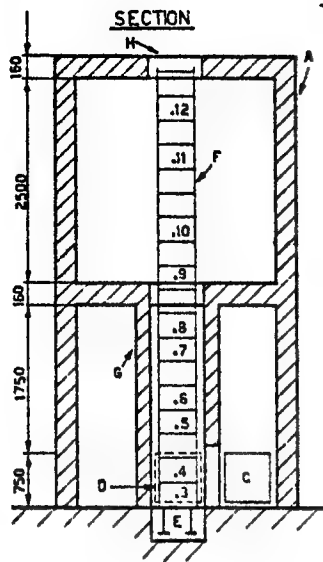


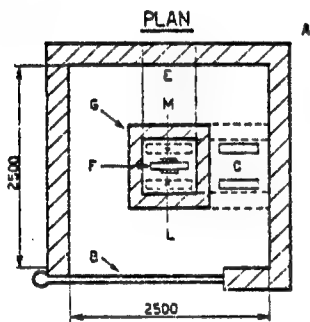
FIG. 4 SWEDISH STANDARD TEST



- A. Concrete structure.
 B. Iron doors.
 C. Furnace in warming-up position.
 D. Furnace in test position.
 E. Air inlet 700x300 mm.
 F. Cable racks.
 G. Chimney.
 H. Opening for fumes.
 I. Cables under test.
 L. Front cable assembly.
 M. Rear cable assembly.

POSITION OF THERMOCOUPLE

| | |
|------|---------------------------|
| 1. 2 | On furnace |
| 3. | 200 mm from ground level. |
| 4. | 630 " " " " |
| 5. | 1100 " " " " |
| 6. | 1530 " " " " |
| 7. | 1960 " " " " |
| 8. | 2390 " " " " |
| 9. | 2670 " " " " |
| 10. | 3370 " " " " |
| 11. | 4220 " " " " |
| 12. | 4670 " " " " |



DETAILS OF FURNACE

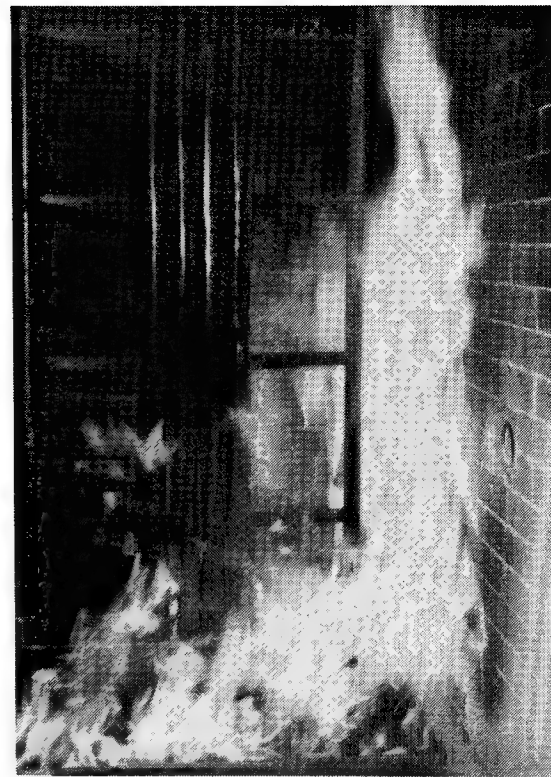
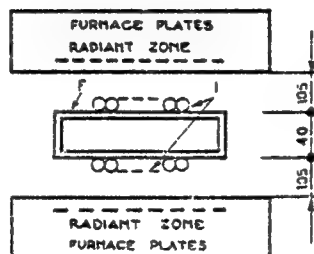


FIG. 6 ALCOHOL IGNITION SOURCE

FIG. 5 ITALIAN STANDARD TEST

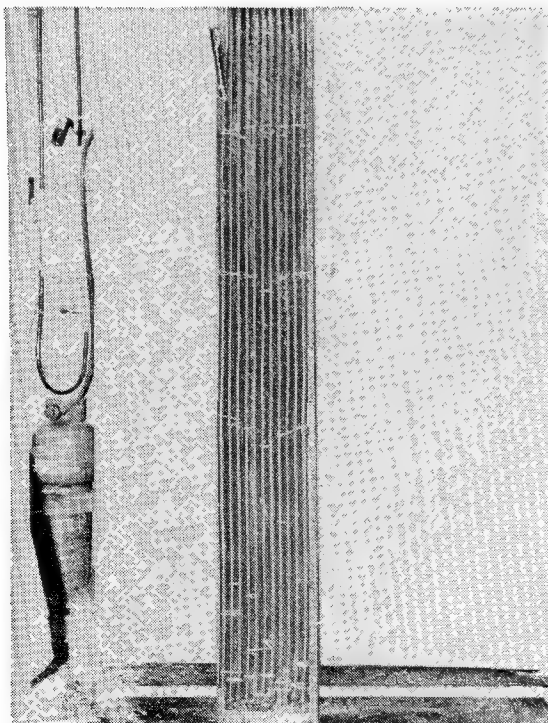


FIG. 7 CABLE SUPPORT RACK

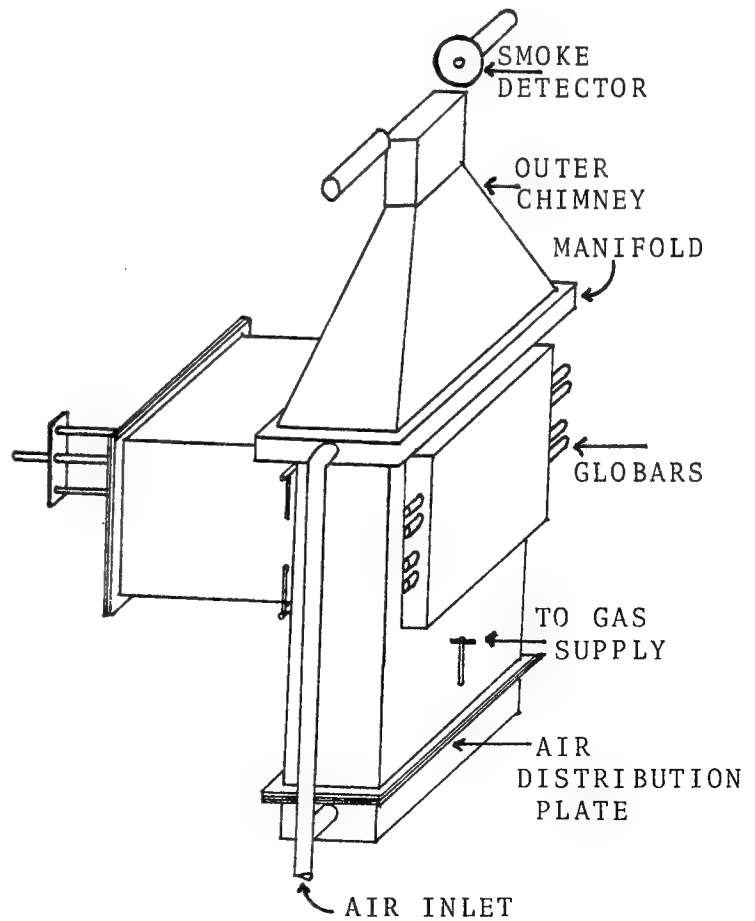


FIG. 8 RELEASE RATE APPARATUS

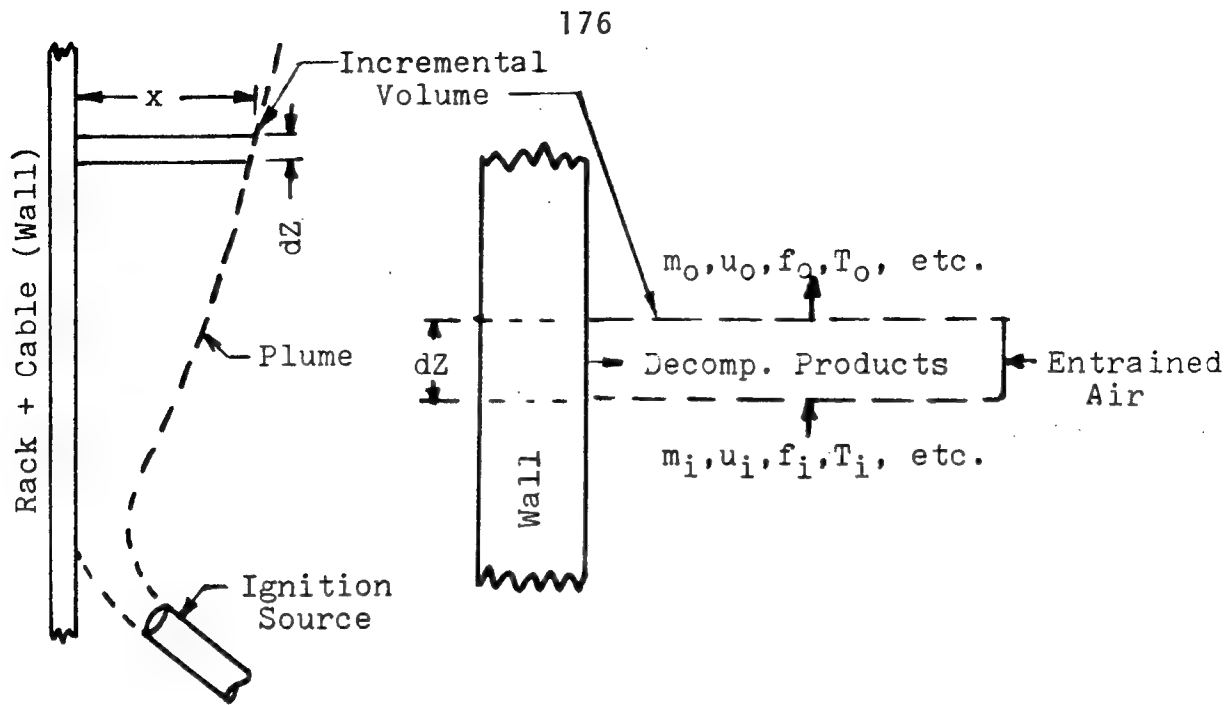
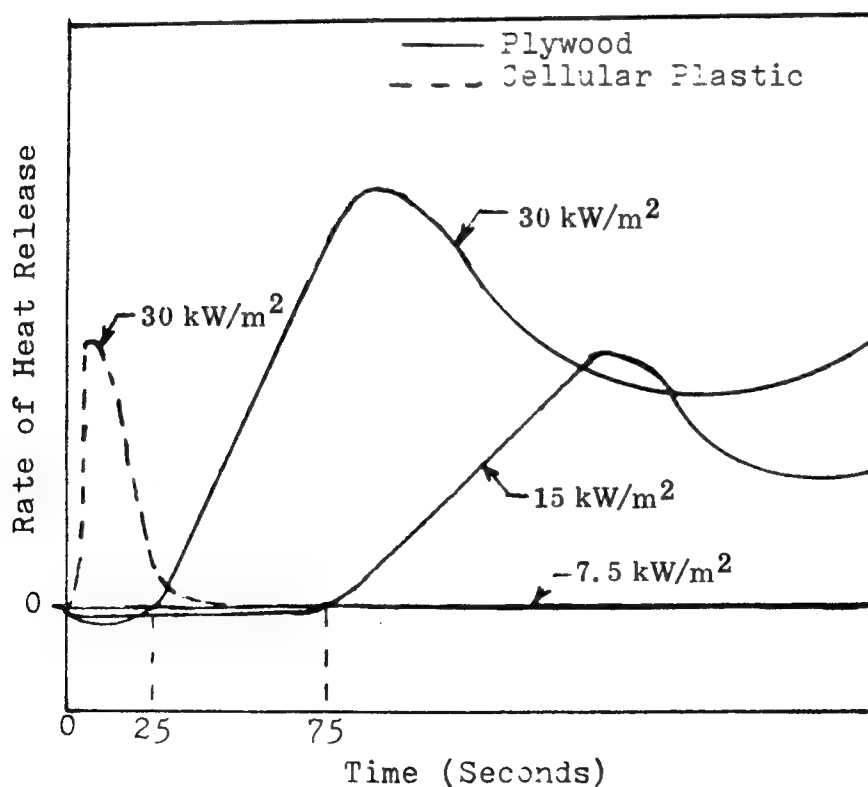


Figure 9: Incremental Volume of Plume



$$FTP_{\min} = (30. - 7.5) \cdot 25 = (15. - 7.5) = 560. \text{ kW, s/m}^2$$

Figure 10: Calculation of FTP_{\min} .

FIG. 11 CONTROL CABLE IN RELEASE
RATE HOLDER

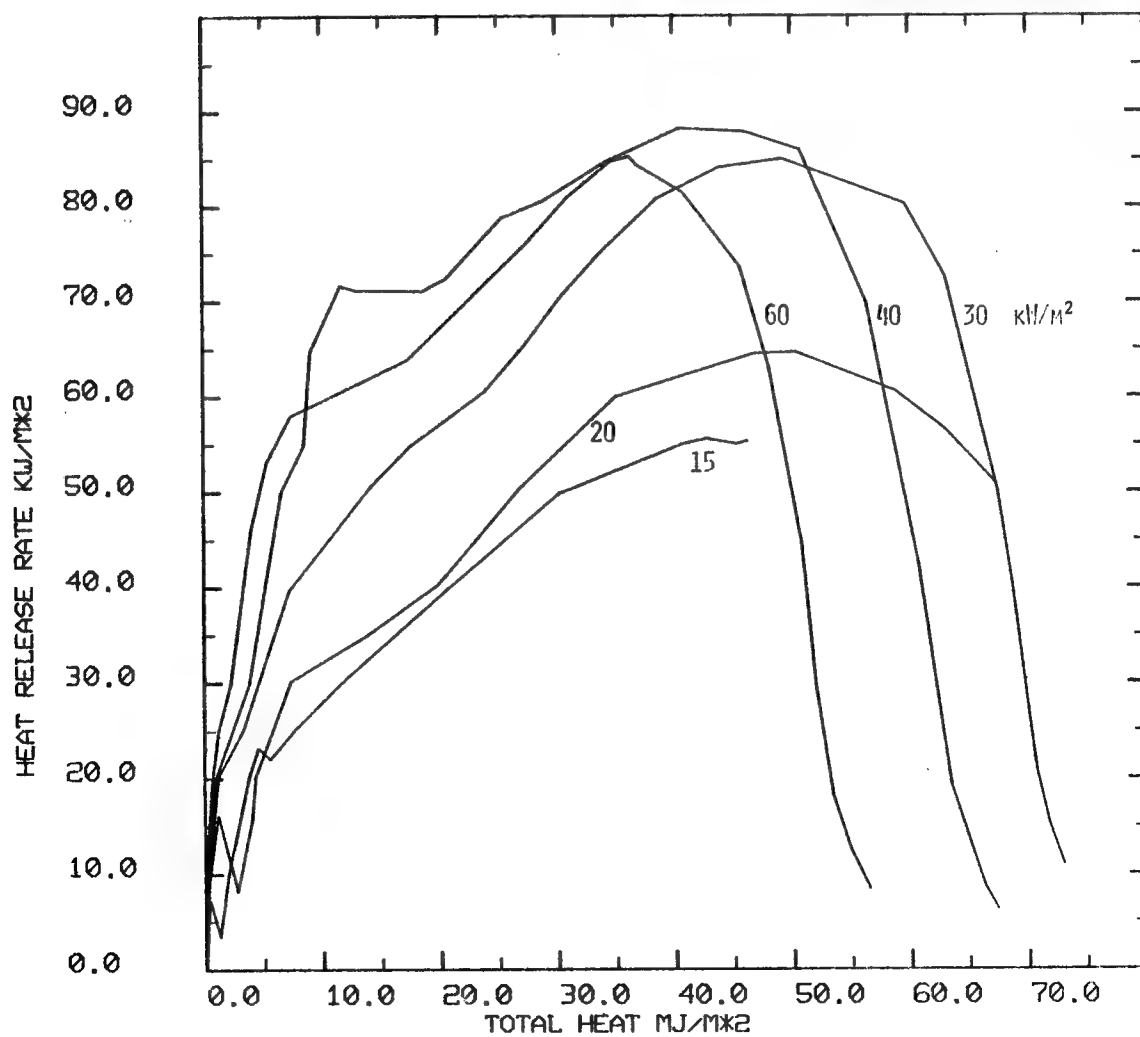
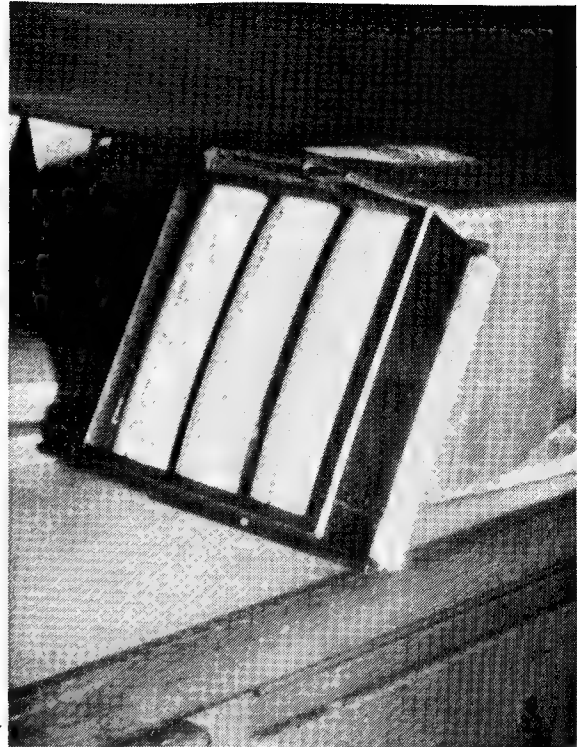


FIG. 12 CONTROL CABLE CURVES FOR MODELLING

FIRE TEST METHOD FOR GRAPHITE FIBER REINFORCED PLASTICS

by Kenneth J. Bowles

ABSTRACT

A potential problem in the use of graphite fiber reinforced resin matrix composites is the dispersal of graphite fibers during accidental fires. Airborne, electrically conductive fibers originating from the burning composites could enter and cause shorting in electrical equipment located in surrounding areas. A test method for assessing the burning characteristics of graphite fiber reinforced composites and the effectiveness of the composites in retaining the graphite fibers has been developed. The method utilizes a modified Ohio State University Rate of Heat Release apparatus. The equipment and the testing procedure are described. The application of the test method to the assessment of composite materials is illustrated for two resin matrix/graphite composite systems.

INTRODUCTION

The relatively recent emergence of advanced technology fibers and resins has greatly increased the potential for the use of composites in the fabrication of primary structures in aircraft. Previously, the application of fiber reinforced composites has been limited to secondary, low stress structures. Graphite reinforced composites are now being considered for highly stressed structural members such as those found in aircraft engine fan frames and ducts. Graphite fibers, used with the recently developed PMR polyimide (ref. 1) represent one of the composite materials of primary interest for these applications. The thermo-oxidative stability of both the fibers and the resin make it possible to use these materials in those sections of aircraft engines where temperatures can reach 500°F (ref. 2). Their combination of very high specific strength and stiffness can result in considerable weight savings in aircraft engines, and thereby lead to significantly decreased fuel consumption.

The graphite fibers used in composite fabrication possess two unique features. They are small in diameter and of low density. These two features allow individual fibers to easily become airborne and to be carried extraordinary distances by air currents. Graphite fibers possess excellent electrical conductivity. Thus, airborne, electrically conductive graphite fibers can create a hazardous environment for electrical and electronic circuitry. In order for such a situation to occur, the fibers must be released from the composite material. This can possibly occur during an accidental fire. Potential hazards from graphite fiber release are described in detail in reference 3, 4, and 5.

The purpose of this paper is to describe a fire test method which can be utilized to assess fiber release characteristics and fiber containment concepts. Fiber containment concepts evaluated in the fire tests included resin structure modification and fiber containment by resin filler materials. The effects of selected

variables such as burning time, char formation and char stability (resistance to oxidation) were evaluated. Burn test requirements for the composites are described as well as test procedures and equipment. Typical results of the burn tests are included. Fiber retention characteristics are assessed primarily by the amount of free graphite fibers visually observed after a sample has been subjected to a standardized burning test.

Burn Test Requirements

The requirements for burn testing the graphite reinforced composites are as follows:

1. A controllable heat source.
2. Reproducibility of burning processes.
3. Graphite fiber dislodgement.
 - a. Air stream
 - b. Mechanical impact
4. Fiber and fragment collection

A controllable heat source is necessary to attain burning reproducibility. A method of monitoring the burning process during the test is necessary for confirming burning reproducibility and for assessing the fire performance of the composites being tested. The "worst condition" for an aircraft has been envisioned as a crash-fire resulting in a fuel-pool fire (ref. 6). The pool fire would envelop at least part of the aircraft. Explosions could occur subsequent to the onset of burning. A model developed for such a situation predicts maximum flame velocities of about 49 feet per second (ref. 7). In order to simulate this series of events in laboratory tests, a controlled airstream across the sample surface and a mechanical impacting device are required. These two features would tend to disturb any free fibers exposed by the burning of the samples and cause them to become airborne.

Equipment

The Ohio State Rate of Heat Release (OSU-RHR) apparatus was chosen as the testing apparatus for the graphite fiber reinforced composites burning test program at the Lewis Research Center. This equipment is shown in figures 1 and 2. The basic design of the equipment provides easy adaptability to produce the versatile research tool required by this type of materials study.

The OSU-RHR apparatus and its operation is fully described in reference 8. The air flowing through the test chamber is heated by the energy released by the burning sample. The amount of heat released by the burning sample is evidenced by an increase in temperature of the outlet gas. By utilizing a heat and mass balance of the air moving through the test chamber, and including the heat losses from the apparatus walls, the heat released by the burning sample can be measured as a function of time.

Some modifications were made to the apparatus to adapt it to the anticipated requirements of the burn tests. Provisions were made for the use of either air or nitrogen as the testing gas. The solid sample holder positioning rod was replaced by a hollow tube. An impacting rod, actuated by an air cylinder, was positioned inside the tubing. The rod was used to impact the back of the composite sample at any desired time during the test. A coarse metal screen (1/8 inch mesh) was positioned in the air exit duct to collect whole fibers which may become airborne during the burning tests. A fiberglass cloth filter over the entrance of the hood ducting was used to trap those fibers and pieces of fibers which might get through the coarse screen. Both filters could be quickly removed and replaced anytime during the test.

A tube, positioned to direct an auxiliary flow of air across the exposed surface of the sample was also installed inside of the test chamber. This air flow system was separate from the chamber air flow required for the heat release determination. The air and nitrogen flow through the burning chamber were metered through rotameter type flow meters. Temperature differences were measured with a thermopile across the air inlet and air outlet ports and the thermopile output was recorded by recorders with a variable chart speed. The radiant heat flux was measured with a radiometer at the beginning of a test and again after the test was completed.

Materials

Burn tests have been conducted using two resin/fiber composite systems. An epoxy/graphite composite (Hercules 3501-6/Hercules HTS-II) was studied because it is typical of the composite material presently being used in the aircraft industry. A polyimide/graphite composite material (PMR-15/HTS-II) was tested because it is one of the advanced technology composite materials.

At this time, the concept of utilizing composite particulate filler materials to retain graphite fibers during burning has been the only design studied to any great extent. Particulate filler materials having a relatively low melting temperature are dispersed in the resin matrix. Heat generated during burning melts the filler allowing flow and encapsulation of the fibers. This type of action would then be expected to cement the fibers together precluding their release during burning. Also, any impact fragments which may be formed would be in the form of large pieces that would unlikely become airborne. The evaluation of this concept requires visual examination of burned sample surfaces for the presence of free graphite fibers. It also requires sample weight change measurement and the demonstration that fragmentation of the burned sample produces only the type of fragments described above.

Figure 3 shows a plot of the results of thermogravimetric analysis of some carbonaceous materials from reference 9. The thermal resistance of two types of fibers (AS fiber and GY-70 fiber) and an epoxy resin are shown in this figure. The difference between the thermal resistances of the two types of fibers can be explained by evidence that the AS fiber is less graphitic than the GY-70 fiber. This figure indicates that fire testing in air at temperatures greater than 1427°F would result in the rapid oxidation of the fibers

along with the matrix. This situation is not desirable since we are looking for the "worst case" conditions where the resin material would be burned completely but the graphite fibers would remain either as free fibers or trapped in the resin/filler char. It is not to be inferred that the fiber material would not degrade. The rate of degradation would be slow in comparison to the degradation of the resin, however. Based on these considerations, the burn tests were conducted at temperatures below 1427°F. Test conditions which provide the desired temperature level for burn tests of graphite fiber reinforced composites were determined to be a radiative heat flux of 5.3 Btu/ft²-sec, with an air flow of 21 cu. ft/min. through the test chamber.

Test Procedure

The air flow through the burn chamber was adjusted to a value of 21 cu. ft/min. through the airline flowmeter. This volumetric flow rate corresponds to a linear flow velocity of 4.2 inches per second over the test sample in the chamber. Figure 4, from reference 6 lists six categories of fibers that have been found after burning and impacting tests. Also listed are the settling rates for these six different fiber categories. Based on these calculated numbers, the air flow rate through the chamber would cause only the single fibers to be carried out of the chamber and to the filtering system. All other fibers which would be in the form of bundles or clumps would fall to the bottom of the burn chamber. The 21 cu. ft/min. air (or nitrogen) flow rate was chosen because it was found to have no effect on RHR measurements (ref. 9). However, it is worth noting that the flow rate can be utilized to separate the single fibers from heavier debris when specimen impacting within the chamber is required.

The gas pilot burner was adjusted to burn 2 cu.ft. per hour of natural gas. The gas pilot served to ignite the volatiles from the sample as they were released.

The silicon carbide heater current was then adjusted until a heat flux of 5.3 Btu/ft²-sec. was attained. Under these conditions, the rate of composite degradation was low enough to allow sufficient time to observe and document the degradation process.

The composite laminates to be burned were cut into 3 in. by 6 in. samples and weighed. The actual resin content of each composite was determined gravimetrically (ref. 10). The thickness of each sample was also measured and recorded.

Each sample was placed into the sample holder of the OSU-RHR apparatus and inserted into the burn chamber. The temperature difference between the chamber inlet air and the outlet air was recorded as the sample burned. All samples remained in the OSU-RHR apparatus for at least five minutes. This was sufficient time to allow sample flaming to cease naturally. The sample was then removed from the apparatus. The filters were removed and visually examined for trapped graphite fibers. The burned composite was weighed, and the exposed surface examined visually for bare graphite fibers. In some instances,

new filters were installed and the sample was reinserted for another period of time. Generally, the sample was reinserted to continue the degradation so as to obtain weight loss data as a function of time. During the second insertion, the auxiliary air flow device or the impacting device could be operated.

Some of the tests were conducted with nitrogen flowing through the test chamber to obtain anaerobic char data.

DISCUSSION

Heat Release

Heat release data and total heat release data provide a history of the burning event to confirm test reproducibility. Also, the data provide a means for comparing the burning processes of different composite materials. Figure 5 shows heat release rate recordings for two types of composite materials included in this study. Figure 5(a) shows the heat release rate curve for a standard bill of material epoxy/graphite composite. Figure 5(b) shows the heat release rate history of graphite/PMR, a polyimide/graphite composite laminate.

Figure 6 shows heat release curves for two panels of graphite/epoxy composite material. Figure 6(a) is that for the standard epoxy/graphite panel and figure 6(b) is the heat release rate curve for similar panel filled with about 10% boron powder. From the appearances of the two curves, there is no significant difference in the two burning processes. These curves were recorded for a burn time of five minutes during exposure to a radiant flux of 5.3 Btu/ft²-sec. Figure 7 shows the surfaces of the two panels. The surface of the panel without the boron filler consists of a mat of loose graphite fiber. The other panel, with the boron filler, exhibits a smooth, shiny surface with no observable loose fibers. While the boron powder does promote retention of the graphite fibers within the solid combustion products of the resin, it does not appear to affect the heat release characteristics during the initial flaming of the sample.

Resin Weight Loss

All resin weight losses from burning were calculated based on the sample weight before burning, the post-test weight, and the as-fabricated resin content of the sample. At least two samples of each type of composite were tested. One was decomposed anaerobically in nitrogen in the OSU-RHR apparatus. The anaerobic testing was performed to assess the results of composite modification in producing a maximum amount of char. It was reasoned that the anaerobic decomposition tests would produce the maximum amount of char for each resin tested. Figure 8 shows weight loss data for the epoxy and polyimide matrix composites for decomposition and burn times up to 35 minutes. For these tests in air, the actual sample flaming time was completed after five minutes of testing. It can be seen in figure 8 that the amount of char available for containing the graphite fibers in the polyimide composites is significantly greater than the amount of char in the epoxy composites after five minutes of burning in air. However, if burning is allowed to continue, the char residue from both

resins disappears. In figure 8, the polyimide produces significantly more anaerobic char than the epoxy resin. Based on these data, neither short time burn tests in air nor anaerobic decomposition tests can be used by themselves as a simplified method for predicting the fiber retention effectiveness of composite systems in air. Figure 9 shows resin weight loss data for three polyimide/graphite composites. One contains a boron powder filler and was burned in air. The other two contained no boron filler. One of these was burned in air and one was decomposed in nitrogen. From the results shown in figure 9, it appears that the boron powder causes the composite to burn anaerobically, possibly by oxidizing, then melting to form a molten B_2O_3 coating which protects the resin char. This type of residue appears to be very effective in retaining graphite fibers as illustrated in figure 7.

Fiber Release

Burn tests with 21 cu. ft. of air flowing through the burning chamber resulted in the collection of insignificant amounts of graphite fibers in the filtering system, even when the sample surface was covered with a heavy layer of loose fibers. Apparently, the disturbance caused by the air flow was not enough to pull individual fibers from the entangled mass of surface fibers. A number of variables have been found to strongly influence fiber release even when the sample was subjected to mechanical impacting and exposure to varying air flows over the surface of the burned sample. These variables and fiber release mechanisms are described in references 11 and 12.

The criterion established in this study for assessing the fiber retention effectiveness was based on the amount of free fibers exposed on the surface of the specimen at the conclusion of the tests. On this basis, only the boron filled composite was effective in retaining the graphite fibers as illustrated in figure 7.

CONCLUDING REMARKS

The burn testing procedures developed for graphite composites provided a semi-quantitative means for assessing burning characteristics and fiber retention effectiveness. These testing procedures also effectively monitored the burning processes and contributed significantly to the understanding of the methods by which fiber containment could be accomplished. The test data were found to be reproducible.

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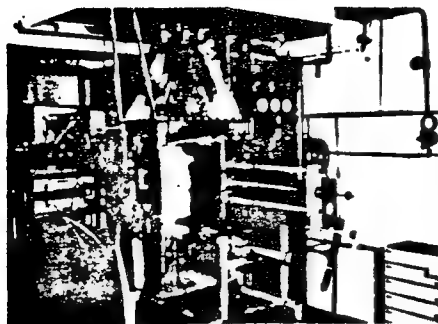


Figure 1. OSU-RHR apparatus

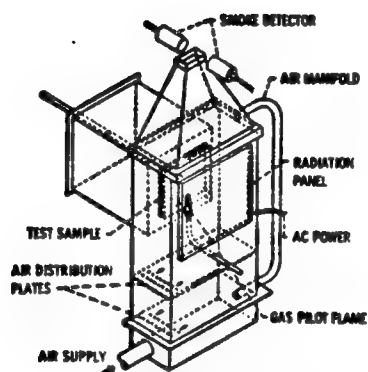


Figure 2. OSU-RHR apparatus

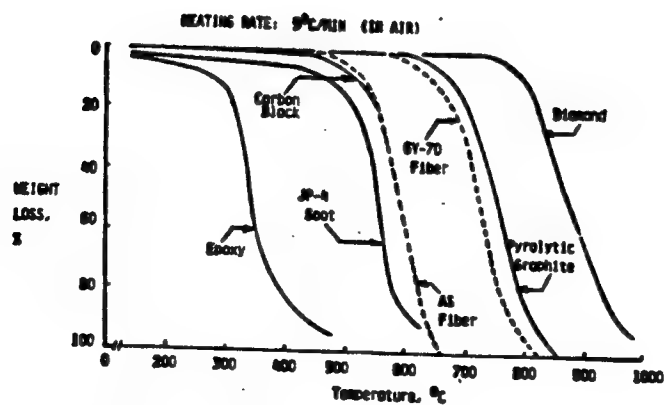


Figure 3. Thermogravimetric analysis of carbonaceous materials

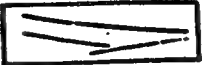

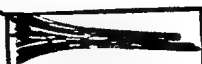
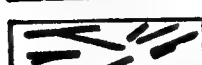


| 186 | | |
|---|---|--------------|
| | Category | Pull Rate |
|  | 1 - Single Fibers | 1.3 in./sec. |
|  | 2 - Lint | 3.7 in./sec. |
|  | 3 - Brush/clump | 35 in./sec. |
|  | 4 - Blast Fragments Width < 2 mm | 60 in./sec. |
|  | 5 - Blast Fragments Width 2-7 mm, Length < 25 mm | 66 in./sec. |
|  | 6 - Blast Fragments Width > 7 mm, Length > 17 mm | 74 in./sec. |

Figure 4. Fiber release categories

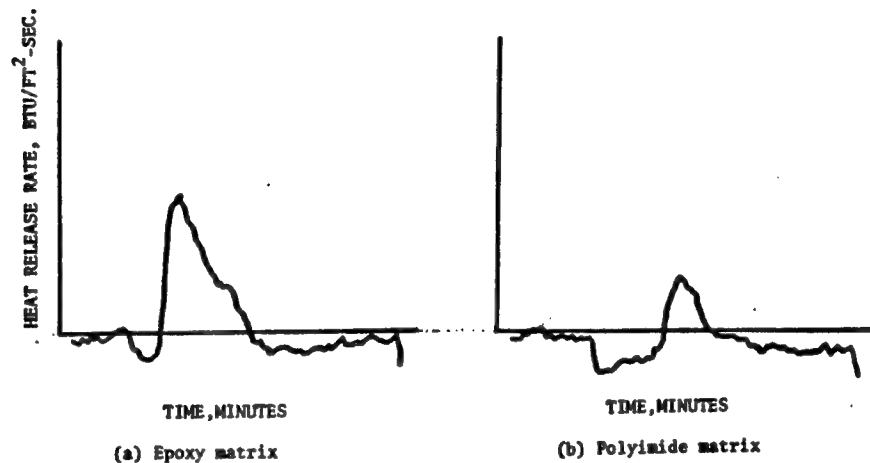


Figure 5. Heat release rate curves for polyimide/graphite and epoxy/graphite composites

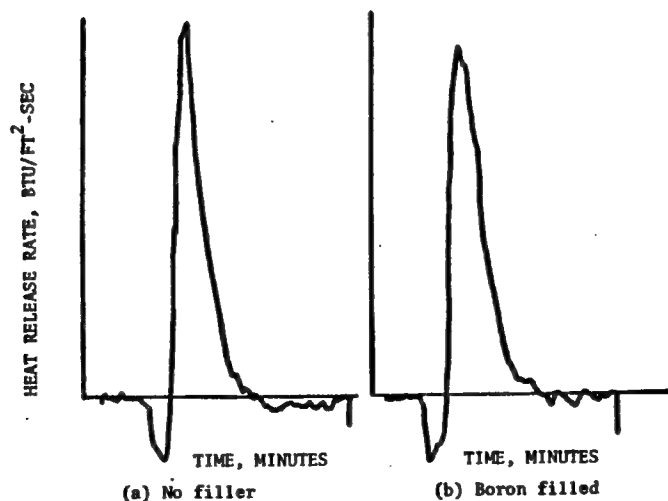


Figure 6. Heat release rate curves for epoxy/graphite and epoxy/graphite/boron composites



Figure 7. Surfaces of epoxy/graphite laminates burned in air by 5.3 BTU/ft²-sec thermal radiation flux

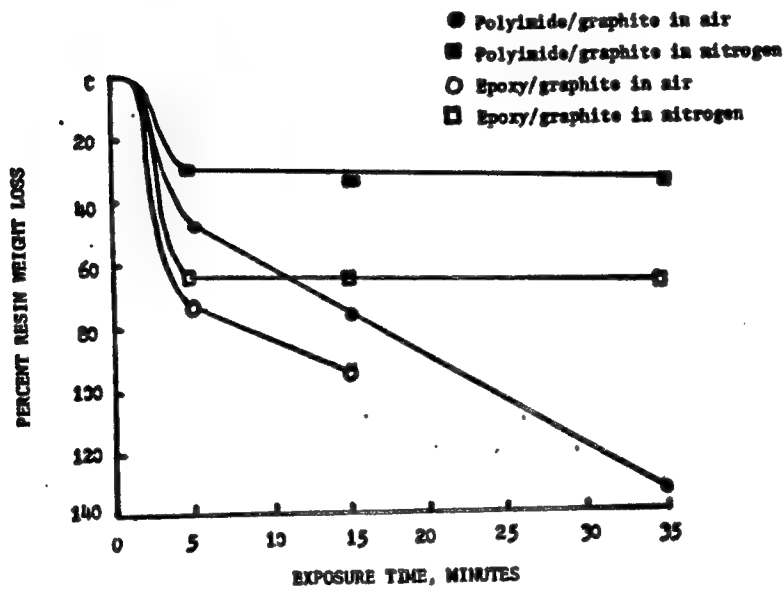


Figure 8. Resin weight loss of laminates during exposure to 5.3 Btu/ft²-sec in air and in nitrogen

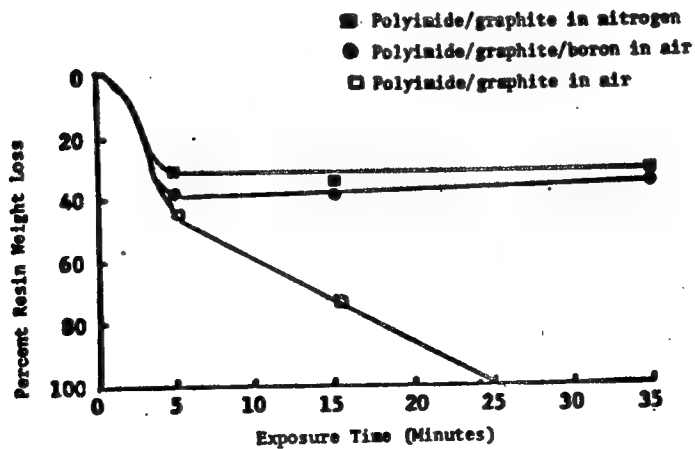


Figure 9. Resin weight loss of laminates during exposure to 5.3 BTU/ft²-sec. thermal radiation

Fire Performance Characteristics in Rooms as the Result
of Increased Insulation: Flashover Conditions

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Abstract

The initial experiments on the fire performance characteristics in rooms as the result of increased insulation were performed at preflashover conditions. The results of this study demonstrated that the level of insulation did not affect the fire performance. The significant factor on the fire performance was the interior wall surfaces. The same room geometry and construction were retained for the flashover fire tests. Two thirty pound wooden cribs were used as the fuel source to produce flashover conditions in the room structure. Multiple fire tests were performed on the structures insulated with faced fibrous glass batts according to Federal Housing Administration (R-19 ceiling, R-11 walls and floor) and energy efficient home (R-38 ceiling, R-19 walls and R-22 floor) recommendations. An uninsulated structure was used as a control. The fire performance characteristics in the test rooms were not influenced by increasing the level of insulation during the flashover tests.

Introduction

The cost and consumption of energy have been increasing at an alarming rate, while the supply of energy has decreased. One way to reduce energy consumption and heating and cooling costs is to increase the insulation levels in homes. Energy conservation measures, however, might conceivably increase the fire hazard potential of a residential structure. This has been alluded to in several articles (1,2,3,4) and proceedings of scientific meetings (5,6). If the fire hazard potential is increased when the insulation levels are increased, this information should be provided to building designers who can design alternate means of achieving fire safety.

One article (3) described fire tests which were performed to evaluate the fire properties for a particular type of building with no insulation as compared with glass fiber, polystyrene, and polyisocyanurate insulation materials exposed to a severe fire source. These conditions were classified as flashover experiments. Flashover (9) can be described as a phenomenon "where suddenly the entire test room is engulfed in flames". In these experiments (3), the insulation materials were installed with their vapor barrier facings exposed. Normally vapor barrier facings are not left exposed but are covered by gypsum board in residential

dwellings. Degenkolb (3) stated that, in his opinion, insulation material, whether combustible or noncombustible, will affect the burning characteristics of a building and its contents.

The results reported by the above article (3) did not relate to residential dwellings because insulation with vapor barriers is covered by gypsum board in these structures. A series of experiments was designed to study the effect of insulation levels on the fire hazard potential of residential structures. The first phase of experiments was concerned with evaluating the fire hazard under preflashover conditions (7). The thermal characteristics of gypsum board lined test rooms without insulation and those insulated to Federal Housing Administration (FHA) and energy efficient home (eeh) recommendations were measured by using a thirty pound fuel source. The results of this study (7) demonstrated that the level of insulation did not affect the fire performance of room structures exposed to preflashover conditions. The significant factor, however, on the fire performance was the interior gypsum board wall and ceiling surfaces.

The objective of the work presented in this paper was to determine the fire performance characteristics of gypsum board lined test rooms exposed to flashover conditions. The thermal characteristics of these room interiors were measured for structures with no insulation and for those insulated to FHA and eeh recommendations. The experimental design of these tests allowed the evaluation of fire performance of rooms with insulation materials installed behind gypsum board rather than exposed to a fully developed fire condition.

Experimental

a. Room Structure

A full-scale room geometry was used to assess the fire performance of rooms with increased insulation. This room geometry has been used extensively in other studies (8), and had interior dimensions of an 8 ft. by 12 ft. floor area with an 8 ft. ceiling height. This room was entirely enclosed with the exception of a 2 ft 6 in. by 6 ft. 8 in. door opening located in the 8 ft. by 8 ft. wall opposite the fuel source. The fire performance of a control structure as well as structures insulated to FHA and eeh recommendations were evaluated. The test rooms were wooden framed structures with gypsum board interior and sheathing exterior. Figure 1 shows the room structure. The fire experiments were performed in the open at ambient air conditions. Each test was repeated twice.

The test rooms were constructed of nominal 2 in. by 4 in. studs on 24 in. centers for the FHA walls, nominal 2 in. by 6 in. studs on 24 in. centers for the eeh walls, nominal 2 in. by 12 in. rafters on 24 in. centers for the floor and ceiling. The interior walls and ceiling areas were covered by 1/2 in. thick regular gypsum board. The interior side of the floor joists and the roof framing were covered by the 1/2 in. thick A-C exterior grade plywood. The exterior side of the wall framing was

covered with one inch thick exterior sheathing board (Georgia Pacific). The gypsum board seams were finished with joint compound and tape.

b. Fuel Source

A fuel source was used which resulted in a flashover phenomenon. The fuel source was two 30 pound wooden cribs (8). Each crib consisted of 60 sticks (nominally 2 in. by 2 in. by 15 in. in length) fastened into 12 tiers with 5 sticks in each tier. Successive tiers were placed at 90 degrees and secured with 8d nails which were included in the total weight of the crib. The wood was kiln-dried white fir with an average density of approximately 30 pcf, dry weight basis.

c. Insulation

Kraft faced fibrous glass building insulation (Owens-Corning Fiberglas Corp.) was used to insulate the test room structures. Two levels of insulation were used. FHA recommendations (dated 1977) require R-19 for the ceiling, R-11 for the walls and floor, while eeh recommendations require R-38 for the ceiling, R-19 for the walls and R-22 for the floor.

d. Temperature Measurements

Thermocouples were used to monitor the temperature build-up and temperature profile associated with the crib fuel sources. Eleven thermocouples were used to monitor the air temperatures inside the room structures. These positions, as shown in Figure 2, are similar to the thermocouple locations referenced in other studies (8). An additional twenty-three thermocouples were placed in the wall and ceiling cavities to measure the temperature profile. Figure 3 shows the wall, ceiling and floor cavity thermocouple locations.

Table 1 lists the thermocouples' functions and positions. A total of 34 thermocouples was used to monitor the room structures. Three type K (chromel-alumel) 14 gauge (0.063 in. diameter) thermocouples were used above the wooden crib (numbers 1, 2, 3). The thermocouples were placed within 0.5 in. diameter black iron pipes and the bare junction protruded 3 in. beyond the end of the iron pipe. These thermocouples were located over the fuel source at 3, 5, and 7 feet above the floor and within 3 in. of the wall surfaces. Eight type K (chromel-alumel) 28 gauge (0.016 in. diameter) thermocouples were placed within 0.5 in. diameter black iron pipes to measure air temperatures within the room. Eight thermocouples were located one inch from the ceiling and walls at various locations in the room structure. Twenty-three 28 gauge (0.016 in. diameter) type K (chromel-alumel) thermocouples were used to measure the temperature profile through the floor, wall, and ceiling cavities. These thermocouples were stapled to their respective positions. Temperatures were monitored with a Vidar Autodata, Inc. Autodata Eight data acquisition and recording system. Four model 6161 Vi-Scan type K thermocouple cards were used in a model 616 scanner interfaced to the Autodata Eight system. A Texas Instruments (TI) electronic data terminal (model 733 ASR) was interfaced to the Autodata Eight system. The

temperature readings were scanned at one minute intervals and recorded on magnetic tape cassettes by the TI terminal. A computer program was written to reduce the data into temperature versus time plots and to perform averages on each temperature position. The data presented in the results and discussion section represent the mean average temperatures.

e. Test Procedure

A 0.5 in. thick sheet of gypsum board (4 ft. by 8 ft.) was placed on the floor in the corner where the fuel source was positioned. Two thirty pound wooden cribs were placed side by side at the left side rear corner of the room on eight fire bricks (4 in. sq. by 3 in. high) each located at the bottom corner of the crib. The cribs were positioned one inch from the walls (see Figure 3). Two pounds of wooden shavings were placed inside the area outlined by the fire bricks. Eight ounces of technical grade methanol were sprinkled over the wooden shavings. The methanol was ignited electrically by a hot nichrome wire. The temperatures were recorded for 25 minutes after ignition.

Results and Discussion

The criteria for evaluating the fire performance of the room structures are based on the time at which the flashover phenomenon was observed, the air temperature build-up within the room structure, and the temperature profile through the ceiling and wall cavities. Flashover can be described as a phenomenon "where suddenly the entire room is engulfed in flames" (9). This phenomenon has been related to an average air temperature of 1020°F to 1110°F in the upper section of a room structure (8). Since there is no currently accepted standards for residential safety, a ten minute elapsed time period (10) from ignition to flashover in a room has been used as a criterion. These experiments were performed for a 25 minute period in order that the ten minute criterion (10), the time-to-flashover and the time to maximum internal room temperature were exceeded.

The effect of increased levels of insulation on time-to-flashover was found to be essentially nil. Flashover time was determined by observing the time when the hot gas layer at the mid point of the ceiling area one inch from the ceiling surface (thermocouple number 13) reached 1020°F or greater. The room air temperatures which indicated the time of flashover are listed in Table 2. The time-to-flashover was approximately three minutes for the control structure without insulation, approximately five minutes for the structure insulated to FHA levels and approximately four minutes for the eeh insulated structures. If increasing the level of insulation in a structure has an adverse effect on the fire performance, the time-to-flashover would be less for the insulated structures than the noninsulated structure. This was not observed. Since the time-to-flashover was approximately the same for each test structure, it appears that the level of insulation has no effect on the fully developed stages of a fire.

The interior room mean air temperatures measured at ten minutes for the room structures are listed in Table 3. The room structure without insulation was taken as the standard to compare thermal responses with the insulated structures. The heat produced from the cribs was reproducible for each room structure test series. This was shown by the thermal data measured by the crib thermocouple series (nos. 1, 2, & 3).

If increasing the insulation level in a structure did adversely affect the fire performance characteristics then one would expect to observe a greater temperature build-up within the structures as the level of insulation increases. No significant differences in the interior room air temperatures at ten minutes after crib ignition (Table 3) were observed in the test rooms with no insulation and those rooms insulated to either FHA or eeh levels.

Maximum room temperatures are listed in Table 4. During the period of time when these values were reached, flashover occurred (as shown in Table 2). The temperatures in the room structures started to decrease after flashover. As the crib fuel source continued to burn, the room temperatures increased to a second maximum which were lower than those reported in Table 4.

The maximum surface temperatures attained in the structures after flashover occurred are recorded in Table 5. There were no significant differences in the maximum mean surface temperatures for the rooms with no insulation and insulation to FHA and eeh levels. Also, no significant differences were observed in the maximum mean cavity temperatures as measured for the rooms insulated to FHA and eeh levels.

There are, however, significant differences between the maximum mean cavity temperatures as recorded for the room with no insulation as compared to the rooms with FHA and eeh insulation levels. The temperature on the cavity side of the gypsum board was either the same or higher for the insulated rooms as compared to the room with no insulation. The temperature on the interior cavity surface of the sheathing was consistently lower for the insulated structures. These results are given by the data recorded for positions B and C in Table 5. The results are easily explained. Insulation reduces heat transfer to levels below that of free air in a cavity.

Conclusions

Insulation in a test structure had no significant thermal effects as recorded for experiments with a flashover fire. This includes the time to flashover, air temperatures in the structures as recorded at ten minutes after ignition as well as maximum surface temperatures. The data establish that insulation has little effect on internal room surface temperatures in the fully developed stages of a fire.

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TABLE 1

THERMOCOUPLE LOCATION

| <u>Thermocouple Nos.</u> | <u>Position</u> |
|--------------------------|--|
| 1 corner above crib | 3 in. from back and left side wall, 3 ft. from floor above crib. |
| 2 corner above crib | 3 in. from back and left side wall, 5 ft. from floor above crib. |
| 3 corner above crib | 3 in. from back and left side wall, 7 ft. from floor above crib. |
| 4 back wall | on wall, 2 ft. from floor, 3 ft. from left wall. |
| 5 back wall | on wall, 4 ft. from floor, 3 ft. from left wall. |
| 6 back wall | on wall, 6 ft. from floor, 3 ft. from left wall. |
| 7 right wall | 1 in. from ceiling, 1 in. from right wall, 4 ft. from front wall. |
| 8 front wall | 4 ft. from ceiling, 1 in. from front wall, 4 ft. from side wall. |
| 9 front wall | 17 in. from ceiling, 1 in. from front wall, 4 ft. from side walls. |
| 10 front wall | 1 in. from ceiling, 1 in. from front wall, 4 ft. from side walls. |
| 11 floor | on floor, 5 ft. from back wall, 4 ft. from side walls. |
| 12 ceiling | on ceiling, 5 ft. from back wall, 4 ft. from side walls. |
| 13 ceiling | 1 in. from ceiling, 4 ft. from back wall, 4 ft. from side walls. |
| 14 left wall | on wall, 2 ft. from floor, 3 ft. from back wall. |
| 15 left wall | on wall, 4 ft. from floor, 3 ft. from back wall. |
| 16 left wall | on wall, 6 ft. from floor, 3 ft. from back wall. |
| 17 left wall | 4 ft. from ceiling, 1 in. from left wall, 4 ft. from front wall. |
| 18 left wall | 8 in. from ceiling, 1 in. from left wall, 4 ft. from front wall. |
| 19 left wall | 1 in. from ceiling, 1 in. from left wall, 4 ft. from front wall. |
| 20 floor | beneath floor, 5 ft. from back wall, 4 ft. from side walls. |
| 21 left wall cavity | on gypsum board, 2 ft. from floor, 3 ft. from back wall. |
| 22 left wall cavity | on sheathing, 2 ft. from floor, 3 ft. from back wall. |
| 23 left wall cavity | on gypsum board, 4 ft. from floor, 3 ft. from back wall. |
| 24 left wall cavity | on sheathing, 4 ft. from floor, 3 ft. from back wall. |
| 25 left wall cavity | on gypsum board, 6 ft. from floor, 3 ft. from back wall. |
| 26 left wall cavity | on sheathing, 6 ft. from floor, 3 ft. from back wall. |
| 27 back wall cavity | on gypsum board, 2 ft. from floor, 3 ft. from left wall. |
| 28 back wall cavity | on sheathing, 2 ft. from floor, 3 ft. from left wall. |
| 29 back wall cavity | on gypsum board, 4 ft. from floor, 3 ft. from left wall. |
| 30 back wall cavity | on sheathing, 4 ft. from floor, 3 ft. from left wall. |
| 31 back wall cavity | on gypsum board, 6 ft. from floor, 3 ft. from left wall. |
| 32 back wall cavity | on sheathing, 6 ft. from floor, 3 ft. from left wall. |
| 33 ceiling cavity | on gypsum board, 5 ft. from back wall, 4 ft. from side walls. |
| 34 ceiling cavity | on sheathing, 5 ft. from back wall, 4 ft. from side walls. |

TABLE 2

ROOM AIR TEMPERATURES INDICATING FLASHOVER PHENOMENON

(DEGREES FAHRENHEIT)

| Thermocouple Position No. | No Insulation | FHA Insulation | eeh Insulation |
|------------------------------|------------------|-------------------|-------------------|
| 7 Right Wall, 1 in | 1230 (3) | 1180 (5) | 1260 (11) |
| 9 Front Wall, 17 in. | 1070 (3) | 1300 (5) | 1050 (4) |
| 10 Front Wall, 1 in. | 1075 (3) | 1190 (5) | 1160 (11) |
| 13 Ceiling, 1 in. | 1210 (3) | 1085 (5) | 1205 (4) |
| 18 Left Wall, 8 in. | 1105 (2) | 1290 (10) | 1250 (11) |
| 19 Left Wall, 1 in. | 1210 (2) | 1015 (3) | 1250 (4) |

Notes:

The values listed in this table are of the form $m(t)$ where m = average temperature for two measurements and t = time at which temperature is reached in minutes. A statistical analysis was not performed on the data.

TABLE 3

INTERIOR ROOM MEAN AIR TEMPERATURES AT TEN MINUTES
(DEGREES FAHRENHEIT)

| <u>Thermocouple Position</u> | <u>No.</u> | <u>No Insulation</u> | <u>FHA Insulation</u> | <u>eeh Insulation</u> |
|----------------------------------|------------|--------------------------|---------------------------|---------------------------|
| Crib | 1 | 1225 | 1510 | 1715 |
| | 2 | 1130 | 1170 | 1370 |
| | 3 | 1150 | 1210 | 1170 |
| Front Wall | 8 | 220 | 245 | 230 |
| | 9 | 695 | 820 | 790 |
| | 10 | 750 | 740 | 670 |
| Right Wall | 7 | 865 | 810 | 730 |
| Left Wall | 17 | 360 | 295 | 425 |
| | 18 | 875 | 880 | 880 |
| | 19 | 900 | 940 | 875 |
| Ceiling | 13 | 925 | 925 | 1000 |

Notes:

The values listed in this table are of the form m where m = mean temperature for two measurements. A statistical analysis was not performed on the data.

TABLE 4
MAXIMUM ROOM TEMPERATURES
(DEGREES FAHRENHEIT)

| Thermocouple Position | No. | No Insulation | FHA Insulation | eeh Insulation |
|--------------------------|-----|------------------|-------------------|-------------------|
| 1. <u>Air</u> | | | | |
| Crib | 1 | 1400 (4) | 1710 (12) | 1750 (11) |
| | 2 | 1470 (4) | 1400 (6) | 1610 (4) |
| | 3 | 1480 (4) | 1330 (11) | 1345 (11) |
| Front | 8 | 450 (4) | 425 (11) | 360 (9) |
| Wall | 9 | 1075 (4) | 1300 (5) | 1515 (11) |
| | 10 | 1075 (4) | 1195 (5) | 1160 (11) |
| Right | 7 | 1230 (4) | 1180 (5) | 1260 (10) |
| Wall | | | | |
| Left | 17 | 760 (6) | 550 (8) | 1250 (11) |
| Wall | 18 | 1160 (4) | 1290 (10) | 1250 (11) |
| | 19 | 1265 (4) | 1015 (3) | 1250 (4) |
| Ceiling | 13 | 1210 (3) | 1085 (5) | 1205 (4) |
| 2. <u>Surface</u> | | | | |
| Floor | 11 | 400 (7) | 350 (12) | 380 (13) |
| Ceiling | 12 | 1130 (3) | 1060 (10) | 1260 (11) |
| Back Wall | 6 | 1140 (4) | 1095 (9) | 1300 (11) |
| at 6 feet | | | | |
| Back Wall | 5 | 1500 (4) | 1040 (12) | 1070 (11) |
| at 4 feet | | | | |
| Back Wall | 4 | 640 (7) | 470 (11) | 630 (11) |
| at 2 feet | | | | |
| Left Wall | 16 | 1000 (11) | 970 (9) | 1000 (11) |
| at 6 feet | | | | |
| Left Wall | 15 | 1080 (9) | 1060 (11) | 1100 (11) |
| at 4 feet | | | | |
| Left Wall | 14 | 1225 (9) | 1310 (12) | 1520 (11) |
| at 2 feet | | | | |

Notes: The values listed in this table are of the form $m(t)$ where m = average temperature for two measurements and t = time at which temperature is reached in minutes. A statistical analysis was not performed on the data.

TABLE 5

MAXIMUM MEAN CAVITY TEMPERATURES

(Degrees Fahrenheit)¹

| Thermocouple Position Nos. ² | | No Insulation | FHA Insulation | eeh Insulation |
|--|-------|------------------|-------------------|-------------------|
| Floor ³ | A(11) | 400(7) | 350(12) | 380(13) |
| | B(20) | 120(16) | 185(16) | 210(18) |
| Ceiling | A(12) | 1130(3) | 1060(10) | 1260(11) |
| | B(33) | 220(13) | 250(13) | 240(16) |
| | C(34) | 280(25) | 200(25) | 200(25) |
| Back Wall at 6 feet | A(6) | 1140(4) | 1095(9) | 1300(11) |
| | B(31) | 230(14) | 245(14) | 240(14) |
| | C(32) | 210(13) | 125(15) | 150(15) |
| Back Wall at 4 feet | A(5) | 1500(4) | 1040(12) | 1070(11) |
| | B(29) | 230(14) | 225(15) | 230(16) |
| | C(36) | 215(14) | 175(10) | 165(15) |
| Back Wall at 2 feet | A(4) | 640(7) | 470(11) | 630(11) |
| | B(27) | 215(13) | 215(12) | 240(17) |
| | C(28) | 210(13) | 120(14) | 140(16) |
| Left Wall at 6 feet | A(16) | 1000(11) | 970(9) | 1000(11) |
| | B(25) | 260(15) | 250(14) | 250(15) |
| | C(26) | 240(15) | 155(16) | 150(18) |
| Left Wall at 4 feet | A(15) | 1080(9) | 1060(11) | 1100(11) |
| | B(23) | 295(15) | 240(13) | 310(25) |
| | C(24) | 290(15) | 185(10) | 185(12) |
| Left Wall at 2 feet | A(14) | 1225(9) | 1310(12) | 1520(11) |
| | B(21) | 315(14) | 270(15) | 280(15) |
| | C(22) | 310(15) | 130(14) | 170(25) |

Notes:

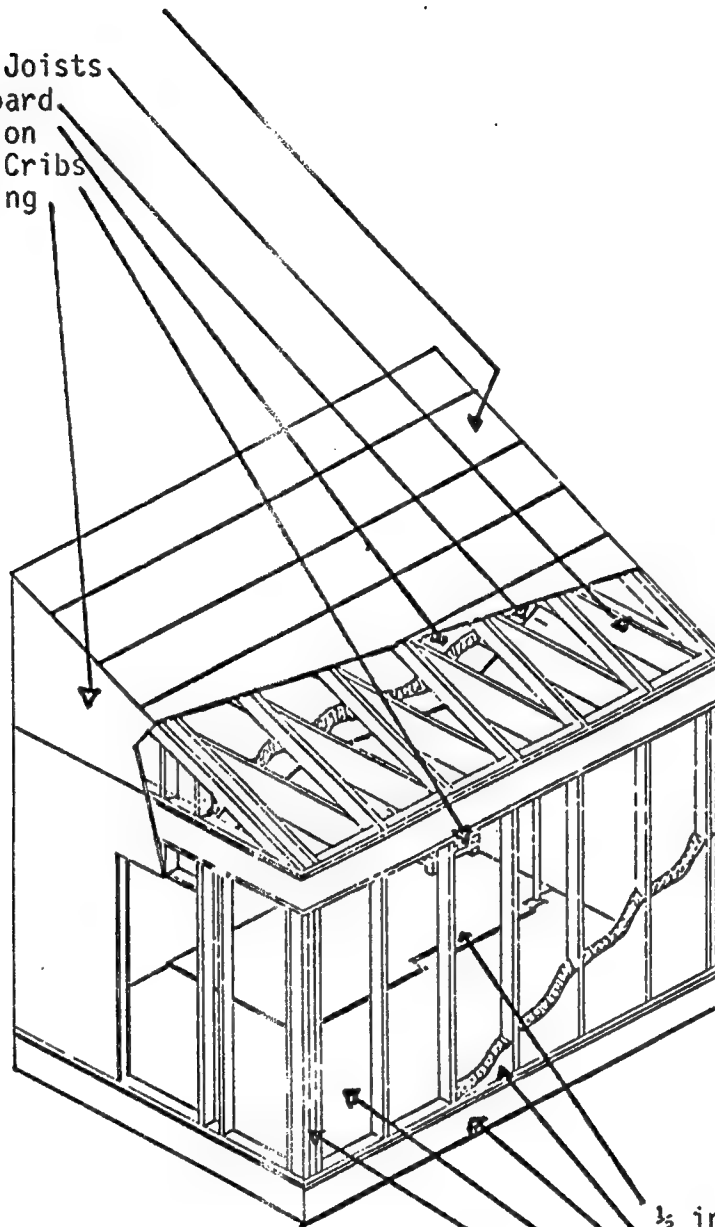
1. The values listed in this table are of the form $m(t)$ where m = mean temperature for two measurements, t = time at which maximum temperature after flashover is reached in minutes. A statistical analysis was not performed on the data.

2. Position A indicates thermocouples which are positioned inside the room on the gypsum board surface; Position B indicates thermocouples

which are positioned inside the cavity on the gypsum board surface; Position C indicates thermocouples which are positioned inside the cavity on the sheathing surface, the (n) refers to the thermocouple numbers.

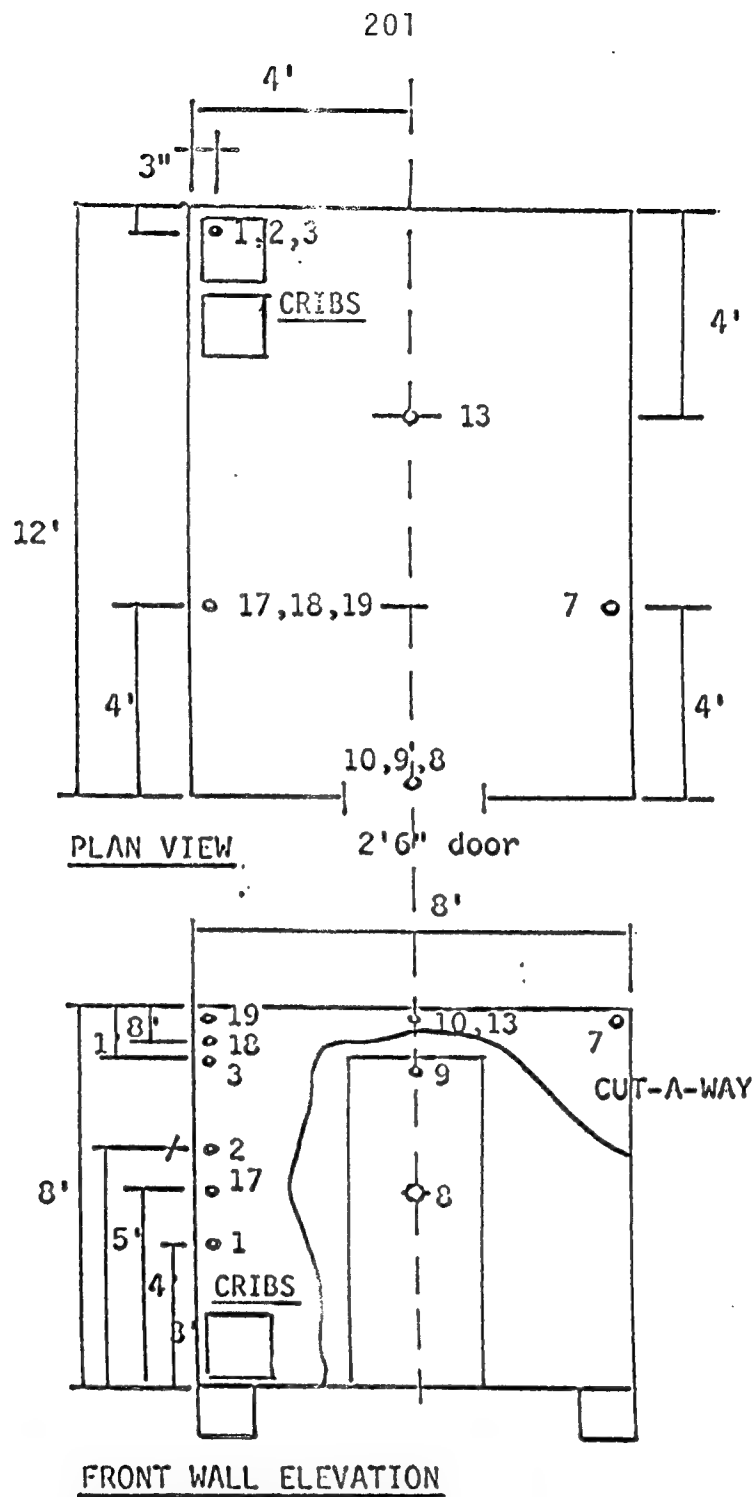
3. Positions A and B for the floor refer to the floor plywood not gypsum board.

Roof material
 2 by 12 Ceiling Joists
 ½ inch Gypsum Board
 Ceiling Insulation
 2 - 30 lb. Wood Cribs
 Exterior Sheathing



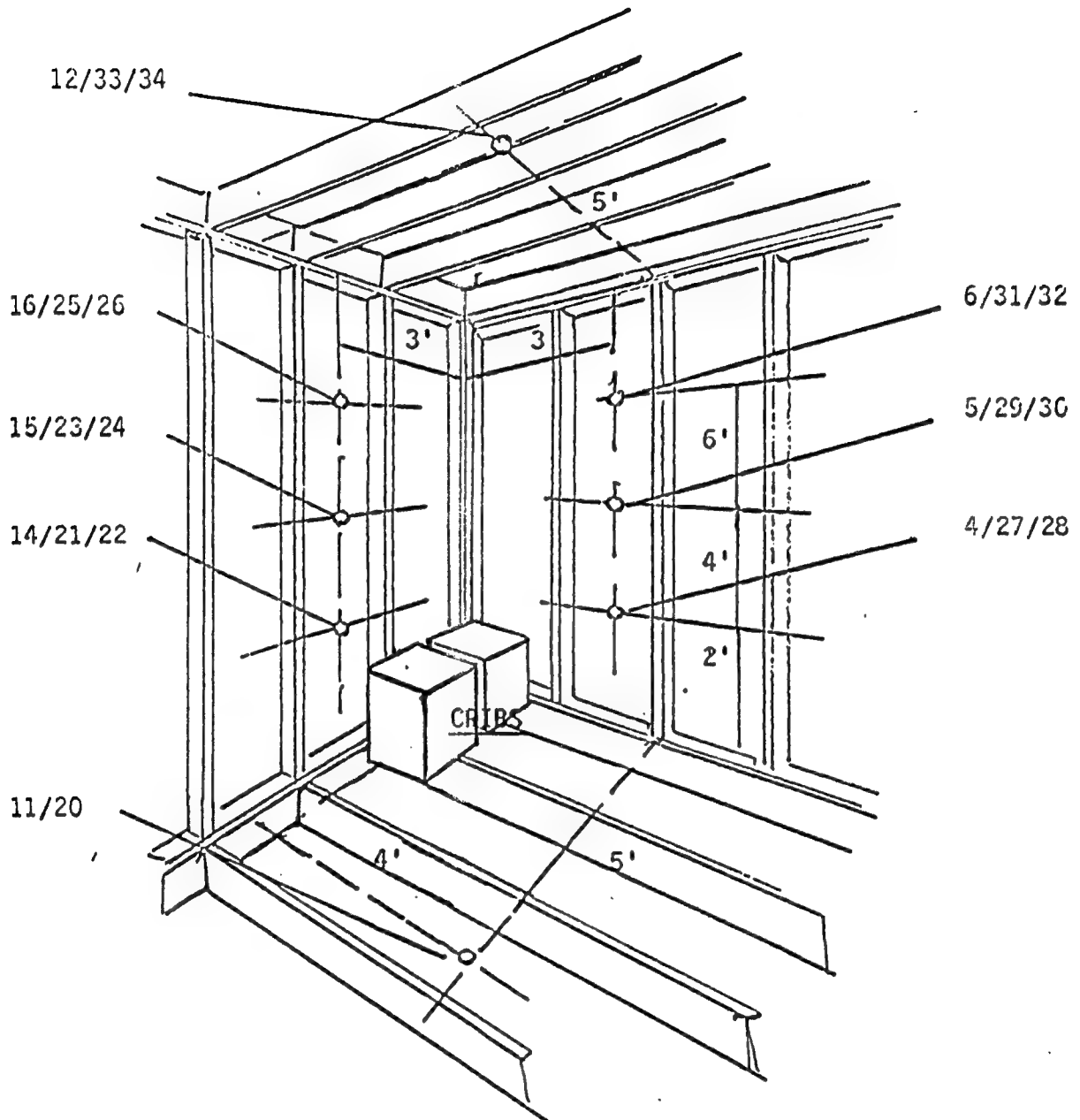
½ inch Gypsum Board
 Wall Insulation
 2 by 10 Floor Joists
 ½ inch Plywood
 Wood Stud Frame*
 *FHA used 2 by 4 studs
 eeh used 2 by 6 studs

FIGURE 1: ROOM STRUCTURE



Thermocouple locations are spaced 1\" from adjacent surface(s), except as noted.
Room dimensions are interior measurements.

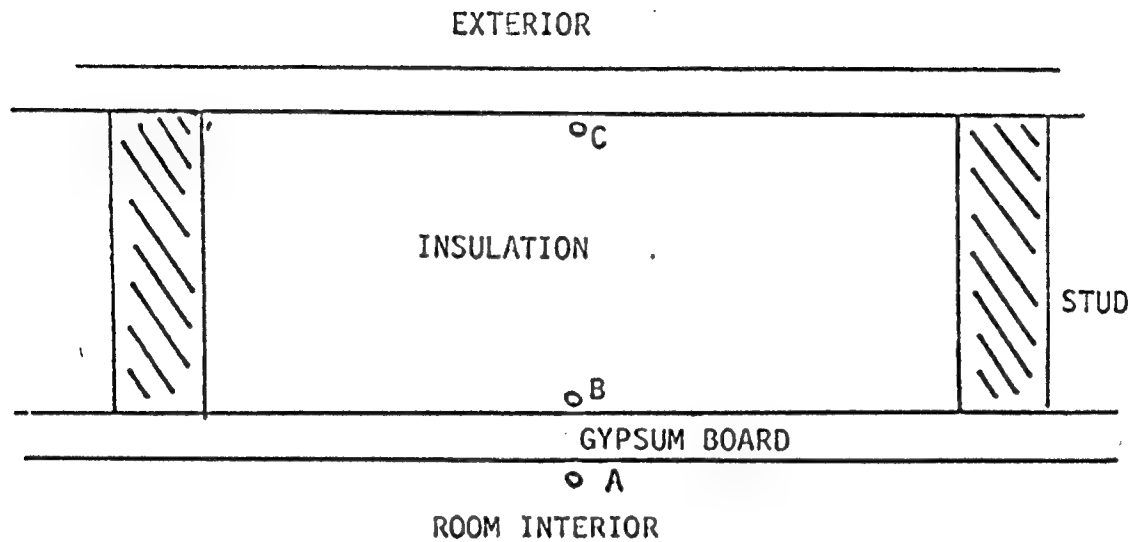
FIGURE 2: THERMOCOUPLE LOCATIONS FOR INTERIOR ROOM TEMPERATURE MEASUREMENTS



Legend A/B/C

A, on gypsum board in room interior; B, on gypsum board surface in cavity;
C, on exterior sheathing surface in cavity.

FIGURE 3: CAVITY THERMOCOUPLE LOCATIONS



Position A indicates thermocouples which are positioned inside the room on the gypsum board surface;

Position B indicates thermocouples which are positioned inside the cavity on the gypsum board surface;

Position C indicates thermocouples which are positioned inside the cavity on the exterior sheathing surface.

FIGURE 4: CAVITY CROSS SECTION

THE EFFECT OF TEST CONDITIONS ON APPARENT SMOKE DENSITY
FROM VARIOUS MATERIALS

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ABSTRACT

Four samples of thermoplastics and nine samples of wood were evaluated for smoke evolution in the Aminco-NBS smoke chamber under piloted (flaming) conditions, using two different types of pilot burners, and in the Arapahoe smoke chamber.

There was no consistent difference in results between the straight and claw design pilot burners with regard to thermoplastics and hardwoods, but the claw design pilot burner resulted in much higher smoke densities with softwoods.

The claw design pilot burner, originally intended to increase the smoke values from thermoplastics, apparently succeeded in increasing the smoke values from softwoods.

Arapahoe smoke values based on initial weight appear to be a cost-effective means of comparing materials for smoke density under flaming conditions.

INTRODUCTION

One aspect of fire performance of materials which directly affects human lives is the density of the smoke produced under smoldering or burning conditions. This affects the ability of the occupants to escape from a burning structure, and the ability of firefighters to effect rescue and control the fire.

The Aminco-NBS smoke chamber is the most widely used laboratory test method for evaluating the smoke evolution from materials, and considerable data has been published using this method (1-4). Most of the published information reports data under piloted (flaming) conditions using the original straight design pilot burner, but a claw design burner is presently used in conjunction with a trough on the front of the specimen holder, to ensure exposure of molten thermoplastics to the pilot flames. In short, the claw design pilot burner was intended to increase the smoke values from thermoplastics. The effect of the pilot burner on the smoke density data from thermoplastics and other materials is therefore of interest.

The Arapahoe smoke chamber has also been used to evaluate various materials (2-6). A comparison of the smoke density data obtained from these thermoplastics and other materials, using the two smoke chambers, is also of interest.

MATERIALS

Four samples of thermoplastics were evaluated in this study. These were identified as:

- P1. polypropylene
- P2. polyethylene, low density, crosslinked
- P3. chlorosulfonated polyethylene
- P4. nylon 66

Nine samples of wood were provided by the Eastern Forest Products Laboratory of the Canadian Forestry Service at Ottawa. Four samples were hardwoods:

- W1. aspen poplar
- W2. beech
- W3. yellow birch
- W4. red oak

Five samples were softwoods:

- W5. western red cedar
- W6. Douglas fir
- W7. western hemlock
- W8. eastern white pine
- W9. southern yellow pine

METHODS

The NBS-Aminco smoke chamber is a completely closed cabinet, 914 by 610 by 914 mm (36 by 24 by 36 in), in which a specimen 76.2 mm (3 in) square is supported vertically in a frame such that an area 65.1 mm (2-9/16 in) square is exposed to heat under either piloted (flaming) or nonpiloted (smoldering) conditions. The heat source is an electric furnace, adjusted with the help of a circular foil radiometer to give a heat flux of 2.5 W/cm^2 at the specimen surface. A vertical photometer path for measuring light absorption is employed to minimize measurement differences due to smoke stratification which could occur with a horizontal photometer path at a fixed height; the full 914 mm (3 ft) height of the chamber is used to provide an overall average for the entire chamber. Each specimen is wrapped with aluminum foil (dull side in contact with the specimen) and the wrapped sample is backed by asbestos board when mounted in the specimen holder.

The Arapahoe smoke chamber (5) consists of a vertical cylindrical combustion chamber 127 mm (5 in) in diameter and 178 mm (7 in) high, a cylindrical chamber stack 76 mm (3 in) in diameter and 457 mm (18 in) high, and a filter assembly at the top of the stack for circular filters 90 mm in diameter. A propane burner is mounted at an angle of 10° from the horizontal in the base of the combustion chamber, and is fed with approximately 90 ml/min of propane to produce a well-defined blue flame about 25 mm (1 in) long. A specimen 38 by 13 by 3 mm (1.5 by 0.5 by 0.125 in) is exposed to the burner flame, and the smoke particles are collected on the surface of the glass fiber filter paper at the top of the stack by drawing air through the filter at an initial rate of 127 L/min ($4.5 \text{ ft}^3/\text{min}$). The specimen is exposed to the burner flame for 30 seconds with air flowing through the filter. The gas is then turned off to extinguish the burner flame, and air flow is continued for an additional 30 seconds to give a total collection time of 60 seconds. The air flow is then turned off and the specimen is extinguished if still burning. The filter is weighed before and after the test to determine the weight of smoke particulates deposited. The specimen is weighed before and after the test to determine the weight of material lost. Smoke is reported as per cent of initial sample or as per cent of material burned. The air flow rate at the end of 60 seconds is recorded as another measure of the amount of smoke deposited on the filter.

RESULTS AND DISCUSSION

The Aminco-NBS smoke test results are presented in Table 1. The data are presented in the form of specific optical density (Ds) at specific times, maximum specific optical density (Dm), and residual specific optical density (Dc). These represent the degrees of obscuration observed at specific times, the maximum degree of obscuration, and the obscuration due to smoke particulates deposited on the surfaces of the optical system, respectively.

In the case of the thermoplastics, there was no consistent difference in results between the straight and claw design burners. Differences, however, could be significant when comparing particular pairs of samples.

The straight burner appeared to be slightly more effective in maintaining flaming conditions. This appears to be due to the fact that the straight burner directs six flamelets on the specimen surface where burning has to be maintained, while the claw burner directs only two flamelets on the same area; the other four flamelets from the claw burner appear more pseudo-scientific but are largely ineffective, two being directed into the trough where any molten material is not exposed to adequate heat flux, and two being directed toward the edge of the specimen holder where the amount of molten material is usually negligible.

In the case of the wood samples, Ds values at any given time were consistently higher when the claw burner was used than when the straight burner was used. In the case of the softwoods, Dm values were significantly higher with the claw burner than with the straight burner; in the case of the hardwoods, the differences in Dm values were not consistent.

The softwoods generally tended to flame less vigorously with time, and to change to smoldering conditions upon extinction of the flame, but the increase in smoke density occurred while flames were still visible. Much of the volatiles from the softwoods appeared to escape burning when the claw burner was used, and contribute to the accumulated smoke. Smoke values from wood have been found to be generally higher with nonpiloted ignition (3,4), and inadequately piloted ignition appears to give similar results.

The authors did not make the optional correction for smoke deposited on the optical system, because they consider the density correction an artifact that is unrealistic and misleading. Smoke deposited on the optical system was originally in the atmosphere obstructing visibility, and the use of the density correction gives a reward for producing smoke that is heavier and more prone to deposit on the eyes and in the respiratory system.

The smoke test results obtained with the Arapahoe chamber are presented in Table 2. Smoke is reported based on initial weight and based on weight loss. The values given are mean \pm standard deviation between experiments.

Air flow rate at the end of 60 seconds may be a rapid method of estimating smoke deposit. Smoke weight, both based on initial weight and based on weight loss, appears to have a relationship to air flow rate. The rate of change in air flow rate during the 60 second test may provide an indication of the rate of smoke production at different times during the test.

The wood samples sometimes exhibited smoldering for time intervals ranging from a few seconds to about 30 seconds. Because blowing air on the sample only increased smoldering and using water to extinguish the smoldering would have altered the sample weight, the smoldering was permitted to continue until it ceased. The weight losses recorded may therefore be slightly greater than the weight losses corresponding to the smoke produced.

The thermoplastics sometimes exhibited dripping. The molten material was recovered and added to the remaining sample when determining the final weight of sample, but the extent of dripping was not constant.

Because of the variations introduced by smoldering of cellulose and dripping of thermoplastics, the authors consider smoke based on weight loss to be much less reliable than smoke based on initial weight.

To provide comparisons, specific optical density data obtained with the Aminco-NBS smoke chamber are presented in Table 2. D_s values at 1 and 2 minutes, and D_m values, are reported. The values given are mean \pm standard deviation between experiments. The test data for each thermoplastic were combined, regardless of pilot burner used, because no consistent difference was observed, but this was not the case with the wood samples, especially beyond 2 minutes into the test.

In the case of the thermoplastics, D_s at 2 minutes appeared to be proportional to Arapahoe smoke weight based on initial weight.

Arapahoe smoke values based on initial weight appear to be a cost-effective means of comparing materials for smoke under flaming conditions.

CONCLUSIONS

The pilot burner used in the Aminco-NBS smoke chamber can significantly affect the test results under piloted (flaming) conditions. The claw design burner is a politically motivated artifact which is inadequate for its alleged purpose; although it has resulted in a certain amount of poetic justice, it should be eliminated and replaced with the original straight design pilot burner.

Arapahoe smoke values based on initial weight appear to be a cost-effective means of comparing materials for smoke density under flaming conditions.

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Table 1. Specific Optical Density (Ds), Maximum Specific Optical Density (Dm), and Residual Specific Optical Density (Dc) Values

| sample no. | pilot burner | test reference | Ds | | | | | | | | | | Dm | Dc |
|------------|--------------|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|-----|----|
| | | | 1 min | 2 min | 3 min | 4 min | 5 min | 6 min | 7 min | 8 min | 9 min | 10 min | | |
| P1 | straight | CJC-152 | 1 | 13 | 40 | 52 | 77 | 112 | 130 | 147 | 150 | 149 | 151 | 7 |
| | | CJC-167 | 1 | 11 | 44 | 54 | 68 | 77 | 78 | 77 | 77 | | 78 | 5 |
| | claw | CJC-160 | 1 | 27 | 71 | 98 | 106 | 116 | 121 | 123 | 122 | | 124 | 11 |
| | | CJC-164 | 1 | 14 | 37 | 44 | 69 | 87 | 97 | 104 | 108 | | 109 | 4 |
| P2 | straight | CJC-154 | 1 | 3 | 13 | 27 | 42 | 64 | 75 | 80 | 81 | 79 | 81 | 4 |
| | | CJC-169 | 1 | 8 | 19 | 21 | 37 | 54 | 60 | 61 | 61 | | 61 | 3 |
| | claw | CJC-158 | 1 | 5 | 34 | 66 | 87 | 107 | 123 | 139 | 145 | 149 | 150 | 11 |
| | | CJC-165 | 1 | 3 | 11 | 36 | 66 | 88 | 113 | 136 | 147 | 156 | 165 | 3 |
| P3 | straight | CJC-170 | 65 | 379 | 560 | 577 | 586 | | | | | | 595 | 19 |
| | | CJC-180 | 129 | 352 | 485 | 532 | 557 | 560 | | | | | 566 | 38 |
| | claw | CJC-175 | 107 | 348 | 475 | 545 | | | | | | | 664 | 23 |
| | | CJC-179 | 36 | 236 | 422 | 704 | 759 | | | | | | 763 | 34 |
| P4 | straight | CJC-172 | 1 | 7 | 13 | 23 | 35 | 44 | 48 | 53 | 60 | 66 | 67 | 5 |
| | | CJC-181 | 1 | 7 | 24 | 42 | 47 | 59 | 73 | 77 | | | 77 | 6 |
| | claw | CJC-174 | 0 | 4 | 11 | 16 | 21 | 28 | 38 | 49 | 55 | 59 | 59 | 3 |
| | | CJC-177 | 1 | 3 | 10 | 23 | 34 | 38 | 43 | 45 | 46 | | 46 | 4 |

Table 1. continued

| sample no. | pilot burner | test reference | Ds | | | | | | | | | | Dm | Dc |
|---------------|-----------------|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|-----|-----|
| | | | 1 min | 2 min | 3 min | 4 min | 5 min | 6 min | 7 min | 8 min | 9 min | 10 min | | |
| W1 | straight | RMM-620 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 2 | 2 | 138 | 1 |
| | claw | RMM-616 | 1 | 1 | 1 | 2 | 6 | 12 | 19 | 27 | 29 | 26 | 29 | 1 |
| W2 | straight | RMM-620 | 0 | 0 | 0 | 1 | 3 | 5 | 7 | 11 | 15 | 18 | 19 | |
| | claw | RMM-616 | 0 | 0 | 0 | 3 | 11 | 18 | 27 | 29 | 29 | 34 | 34 | 1 |
| W3 | straight | RMM-619 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 3 | 2 | 2 | 3 | 1 |
| | claw | RMM-616 | 0 | 0 | 0 | 0 | 1 | 3 | 9 | 23 | 20 | | 23 | 1 |
| W4 | straight | RMM-619 | 0 | 0 | 0 | 0 | 1 | 4 | 9 | 15 | 13 | | 15 | 1 |
| | claw | RMM-616 | 0 | 0 | 1 | 8 | 23 | 29 | 35 | 41 | 41 | 36 | 42 | 0 |
| W5 | straight | RMM-619 | 1 | 5 | 14 | 24 | 38 | 46 | 52 | 59 | 63 | 67 | 134 | 211 |
| | claw | RMM-616 | 6 | 2 | 40 | 81 | 131 | 165 | 187 | 200 | 213 | 222 | 259 | |
| W6 | straight | RMM-619 | 0 | 0 | 5 | 20 | 40 | 55 | 67 | 75 | 79 | 80 | 81 | 0 |
| | claw | RMM-616 | 6 | 28 | 58 | 102 | 184 | 296 | 381 | 433 | 468 | 487 | 503 | |
| W7 | straight | RMM-619 | 0 | 0 | 4 | 9 | 17 | 25 | 34 | 41 | 47 | 53 | 112 | |
| | claw | RMM-616 | 0 | 3 | 27 | 64 | 92 | 152 | 208 | 253 | 233 | | 253 | 2 |
| W8 | straight | RMM-619 | 0 | 1 | 4 | 9 | 17 | 27 | 36 | 45 | 53 | 60 | 136 | 1 |
| | claw | RMM-616 | 0 | 9 | 30 | 63 | 106 | 150 | 191 | 232 | 281 | 289 | 359 | 2 |
| W9 | straight | RMM-619 | 0 | 0 | 0 | 1 | 3 | 7 | 8 | 7 | | | 9 | 1 |
| | claw | RMM-616 | 0 | 1 | 1 | 6 | 26 | 59 | 81 | 106 | 138 | 169 | 444 | |

Table 2. Smoke Test Results with Arapahoe and NBS-Aminco Chambers

| sample no. | Arapahoe Chamber | | NBS-Aminco Chamber | | | |
|---------------|-----------------------------------|-------------------------|----------------------------------|-------------|--------------|--------------|
| | smoke, per cent initial weight | based on weight loss | air flow ft ³ /min | Ds 1 min | Ds 2 min | Dm |
| P1 | 0.349 ± 0.046 | 1.258 ± 0.254 | 3.9 ± 0.2 | 1.0 ± 0 | 16.2 ± 7.3 | 115.5 ± 30.4 |
| P2 | 0.203 ± 0.031 | 0.998 ± 0.161 | 4.5 ± 0 | 1.0 ± 0 | 4.8 ± 2.4 | 114.2 ± 51.0 |
| P3 | 4.026 ± 0.571 | 18.226 ± 0.767 | 3.4 ± 0.1 | 84.2 ± 41.7 | 328.8 ± 63.3 | 647.0 ± 87.6 |
| P4 | 0.052 ± 0.011 | 0.644 ± 0.160 | 4.5 ± 0 | 0.8 ± 0.5 | 5.2 ± 2.1 | 52.2 ± 13.1 |
| W1 | 0.132 ± 0.018 | 0.204 ± 0.027 | | 0.5 | 0.5 | |
| W2 | 0.052 ± 0.025 | 0.083 ± 0.040 | | 0 | 0 | 26.7 ± 10.5 |
| W3 | 0.087 ± 0.028 | 0.144 ± 0.042 | | 0 | 0 | |
| W4 | 0.107 ± 0.047 | 0.179 ± 0.077 | | 0 | 0 | 28.4 ± 19.1 |
| W5 | 0.230 ± 0.074 | 0.346 ± 0.115 | | | | |
| W6 | 0.141 ± 0.029 | 0.239 ± 0.047 | | | | |
| W7 | 0.199 ± 0.080 | 0.330 ± 0.135 | | 0 | | |
| W8 | 0.172 ± 0.038 | 0.273 ± 0.064 | | 0 | | |
| W9 | 0.081 ± 0.036 | 0.123 ± 0.054 | | 0 | 0.5 | |

TESTING OF MATTRESS MATERIALS UNDER SIMULATED ARSON CONDITIONS

by

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ABSTRACT

A brief history and description of a new foamable, hydrophilic polyurethane serves as an introduction to a description of a search for better small scale flammability tests for cellular plastics. Test results from the use of an inverted oxygen index method led to a different perspective on the use of external heating vs increasing the heat feedback for small tests.

The results for three new tests that simulate arson conditions are reported for nine mattress core materials. The first test, essentially burning a small slab treated with paint solvent, proved to be a relatively mild and sometimes misleading test. The second, a rolled mattress configuration, proved to be more vigorous but is very inconvenient and expensive to carry out. The third, a smaller version of the mattress roll-up test is also a vigorous test but is a practical and much more convenient protocol for general use, and we are working to develop it as a screening burn test and a quality control procedure.

INTRODUCTION

In 1971, while searching for new paper wet strength agents, a chemist at our research center discovered that one of his intermediate materials formed a soft, surprisingly strong foam when he added it to water. Subsequent work modified the product enough to make it useful for converting to foams now used in a number of commercial applications such as in personal care, health care, and household products. This unique material, an isocyanate terminated liquid polyurethane, was given the trade name HYPOL® FHP (Foamable Hydrophilic Polyurethane) Polymer.

This new product was found to be very different from conventional polyurethanes. The polymer's relatively high ethylene oxide content permits and, in fact, mandates the use of massive amounts of water during the foam forming reaction. Acceptable foams can be produced using from 50 to 200 parts of water per 100 parts of prepolymer (1). This can be contrasted with conventional urethanes that use close to stoichiometric amounts of water, typically 2 to 5 parts per hundred, during the foaming step. The literature teaches that the use of excess water, e.g., 4 to 10 parts per hundred, leads to unacceptable foams (2), but by the time we became aware of this teaching we realized it isn't always true.

Obviously, this large excess of water must be removed after foaming to develop acceptable properties, and this inconvenience may have been one of the factors mitigating against prior commercial development of this type of material. In addition, the technique requires the formation of a prepolymer which was and still is counter to the popular trend towards one-shot urethane foam systems.

At any rate, we were able to develop the necessary techniques to find niche markets for these new hydrophilic foams that can be formulated to range in texture from sensually soft to rigid. For a period of two or three years, most of the development work had been aimed only at specialty hydrophilic foam markets. Very little work was done on attempting to apply these foams to fire-resistant applications.

EARLY FLAMMABILITY WORK

I must confess I was one of the main stumbling blocks in postponing work on fire retardance research involving these new materials. We knew at an early date that the foam looked good on such flammability procedures as ASTM D-1692 and the DOT MVSS-302 Tests, but this could be ascribed to its hydrophilic behavior and to its facile thermal melting behavior. In addition, we discovered early in the game that conventional halogen-containing additives didn't improve the flammability resistance. Addition of high surface area particulate solids like bentonite, that eliminate the melting behavior, led to a much more flammable foam.

It wasn't until a consultant urged us to quantify the relative flammability of our material with oxygen index (O.I.)

measurements that we started thinking in terms of having in these foams a potentially useful new property (3). Table I shows the type of data we compiled at this time. Of course, I felt then and still feel that O.I. data on materials that melt must be viewed with suspicion. Unfortunately, these data were not developed with the more reliable mass burning rate technique that will be described in Dr. Ron Petrella's talk tomorrow (4), but it is an historical fact that these data started us on a search for less flammable foam products. Note also from Table I the effects that different surfactants and wet conditioning have on these values.

Shortly thereafter we started adding hydrated alumina to the foam. This was easily accomplished by suspending it in the large aqueous phase used in foaming. Table II shows a fascinating synergism that we observed when both alumina trihydrate and phosphorus additives were included in the formulation. These results were so unexpected that we cleaned and recalibrated the O.I. apparatus before believing the result. Until recently, we haven't known how to make acceptably strong foams with O.I. values above 60%, so at that time we "retreated" to formulations that measured at only about 40%.

Still the nagging thought that O.I. measurements were misleading forced us to use tests normally applied to rigid foams such as Mobil 45° Test and Butler Chimney (ASTM D-3014-74). Work done at Celanese by D. E. Stuetz and coworkers provide still another test method that seemed appropriate (5). These workers essentially inverted the O.I. test, i.e., they lighted the specimen at the bottom and foiled dripping behavior by placing an absorptive wick through the center of the specimen. It took us two or three months to develop such a technique that would provide reproducible data. Table III shows values obtained for a few of the more than 40 foams tested by this procedure. You will note that all the inverted O.I. values (I.O.I.) are lower, as expected, but we were somewhat disconcerted to observe that our foam dropped 10 points in value, as compared to much smaller dropoffs for conventional foams (6).

The reason for this drop in I.O.I. is apparent if one analyzes the character of the burning conditions in the inverted test. Consider a very simple burning model where q_d is the heat required to degrade a polymer, q_c is the heat produced in the flame when the polymer is burned, and q_f is fraction of q_c that feeds back to the polymer. Heat losses from the flame and polymer may then be labeled q_{cl} and q_{dl} .

With equilibrium burning, as one establishes with the oxygen index test, $q_f = q_d + q_{dl}$ (A); q_f is only a fraction of q_c , i.e., $q_f = xq_c$ (B). Substituting xq_c in equation (A) and rearranging, we get $q_c = \frac{1}{x} q_d + q_{dl}$. Note that q_c is proportional to the O.I. value so if we plot O.I. vs q_d we get a straight line. Note that x for an inverted O.I. is larger, so the slopes for O.I. and I.O.I. data are as shown in Figure 1 (7).

The above treatment implies that if we plot any test data vs the heat required to degrade the polymers, we can develop straight line plots whose slope is proportional to the heat flux created in that particular test. If we design tests with very high heat fluxes, we are going to create tests with response lines whose slopes approach zero. In brief, this implies that a tougher test requires a more sophisticated test response measurement.

This method of plotting the data is a handy way to explain to the uninitiated why some tests do a poor job of differentiating among various materials and why many small scale tests do not simulate real fire situations.

Another facet of this treatment can be seen in Figure 2. If one assumes that regular O.I. values approximate the q_c of materials, then plotting modified O.I. values as the ordinate provides a comparison of tests where the heat flux is increased via feedback vs those where external heating is used to modify the O.I. values. Plotted here are data from our I.O.I. experiments and from a paper by J. DiPietro and H. Stepniczka (8). These workers preheated the specimens to make the test more rigorous. Note that heating to 125°C made the test only slightly tougher, whereas heating to 300°C gave an effect similar to our inverted oxygen index configuration.

SIMULATED ARSON TESTING

From analysis of the above laboratory fire test procedures, it became apparent to us that we had indeed formulated a new product having outstanding flame spread resistance. In searching for commercial outlets, it was therefore logical for us to consider usage as cushioning and bedding products in remote egress areas and arson susceptible locations. The product seemed especially suitable and attractive for application in institutional markets such as dormitories, mental hospitals, detention centers, and various penal institutions. On approaching these potential markets,

we were soon faced with the problem of demonstrating the performance of our modified foam in what our customers call a real life fire situation. Prison officials, for example, want to see how one mattress material will compare with another under some scenario they can perceive to be possible in their institutions. This was an especially sensitive and critical area of concern because by this time conventional urethanes had gotten a bad reputation as a fire hazard, and urethane foams in general had been banned from use in many state funded institutions. We were left with the burden of proving that not all urethanes are necessarily hazardous in a real life situation.

We responded to these challenges by developing a sequence of three different test demonstrations. To date, we have conducted fire tests on ten mattress core types that are summarized with their O.I. values as shown in Table IV. These materials were either supplied by or chosen by officials who supply mattresses to various correctional institutions.

The first and least vigorous of our tests is one we call the Simulated Prison Arson Test. We use the acronym SPAT. This configuration is our modification of a procedure suggested by officials in the New Jersey Bureau of State Use Industries. It involves burning a 15" x 15" square section cut from a mattress core. The ignition source used is eight ounces of VarsolTM paint thinner solvent, which is poured into one corner of the 3" thick test specimen. The configuration of the test setup and the observed results with fire-retarded conventional polyether urethane foam are shown in Figures 3 to 6, and the summary of data taken from all of the nine materials tested is shown in Table V. We conclude from the results observed here, when compared with the two roll-up test configurations that follow, that the SPAT burn procedure is a relatively mild one and can give misleading results in many cases. That is, several of the materials shown here resist flashover in this format but create massive fires when heat feedback is provided or the ignition source is made more severe.

A second procedure we have studied is the Mattress Roll-up Test suggested by officials at the State Prison in Jackson, Michigan. The test configuration is shown in Figure 7. The mattress is rolled end-to-end into a cylinder, tied securely, set upright and tilted at a slight angle from the vertical to provide draft, stuffed with newspapers, and then lit at the bottom. In addition to conducting this test several

dozen times on our cores and on other competitive products, we conducted a statistically designed fractional factorial experiment that investigated the effects of changing the angle and diameter of the roll, the density of newsprint, humidity conditioning of the newsprint and mattress, and the thickness of the mattress cores. From these data we designed a scenario that gives good reproducibility and is very similar to the test shown by Gordon Damant in his Prison Mattress presentation on Monday (9). We use a core diameter of 9 inches, the roll is tilted 30° from vertical, 8 full double page sections of crumbled up newspaper are used after conditioning at 50% relative humidity for 24 hours. The newspaper is ignited from the bottom to intensify the fire and create a chimney effect. Interestingly, we can correlate the performance of our foams in this test with O.I. values, i.e., an O.I. of about 45% is the cutoff point above which candidate materials generally will fare well in the test procedure. Figures 8, 9, and 10 show the roll-up test in progress for three different mattress cores. Figure 8 shows the progress of the fire with a conventional foam similar to material shown by Prof. Williamson yesterday during his talk on the BART fire problem (10). Figure 9 shows the test with the fire-retarded polyester urethane ten minutes into the test, and Figure 10 shows the final results of the test with HYPOL-based foam. A summary of the data obtained for all candidates is presented in Table VI. Although this protocol gives meaningful results, it is very difficult to carry out. Therefore, we developed a simpler model of it which will be discussed next.

The third procedure is possibly the most rigorous of all. It is a small test utilizing a simple and more reproducible ignition source, i.e., Varsol paint thinner solvent, along with the high heat feedback roll-up configuration of the full scale mattress burn test described above. Figure 11 shows the configuration of test and illustrates why we call it the Tear Drop Test. To conduct this test, one folds the 3" x 15" x 30" test piece end-to-end and ties it with two bands of wire. It is then placed on a hardware cloth support with the cylinder in a horizontal position with a support bar pressing down from above to keep it from rolling over. Now the paint solvent, 8 ounces, is poured evenly into the interior bottom portion of the cylindrical shape and ignited with a match. We prefer this procedure, not only because it provides the high heat flux that makes good foams look relatively better, but also because it is safer, smaller, cheaper, and faster to run than the full-size mattress roll-up technique. One can conduct this smaller scale test without taking the

elaborate precautions that are necessary for the full roll-up procedure, different ignition sources or replicate runs can be made from a single mattress, and it shows promise of being more reproducible to conduct. Figures 12, 13, and 14 show the end point response of HYPOL-based foam and the two types of neoprene foams in this test. The summary data for this procedure on the nine different candidates are shown in Table VII. One can see that the results of the Tear Drop Test correlate very well with the results of the full scale mattress roll-up procedure (Table VI).

CONCLUSIONS

In concluding, I would like to emphasize that we do not believe that any of these three techniques should be considered scientifically satisfactory test methods as they now stand. They are really only burn demonstrations and until all the test parameters are defined, the word demonstration is the better way to describe them. Although they do not, nor cannot, replace a scientific measurement such as the rate of heat release, we believe the Tear Drop procedure can be developed into a reliable, reproducible test that would satisfy the relatively unsophisticated needs of typical customers without sacrificing the high heat flux conditions necessary to simulate arson-type fire situations. This will be the general direction of future work carried out in our laboratories.

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TABLE IOXYGEN INDEX VALUES* OF CELLULAR PLASTICS

| | |
|--------------------------------------|--------|
| CONVENTIONAL POLYURETHANES | 15-21% |
| SAME WITH FIRE RETARDANTS | 19-28% |
| HYPOL® -BASED, DRY | 23-25% |
| HYPOL-BASED, CONDITIONED AT 93% R.H. | 25-36% |
| HYPOL-BASED WITH FIRE RETARDANTS | 50-70% |

* THESE VALUES ARE NOT INTENDED TO REFLECT
HAZARDS PRESENTED BY THESE OR ANY OTHER
MATERIALS UNDER ACTUAL FIRE CONDITIONS

TABLE IIMODIFIED HYPOL® -BASED FOAMS*

| <u>ADDITIVES</u> | <u>O.I. (%)</u> |
|--------------------------------|-----------------|
| NONE | 23-25 |
| P-COMPOUND (1-20 PHR) | 25-28 |
| HYDRATED ALUMINA (100-200 PHR) | 30-39 |
| BOTH OF ABOVE | 32-70 |
| PRACTICAL FORMULATION | 40-55 |

* THESE VALUES ARE NOT INTENDED TO REFLECT
HAZARDS PRESENTED BY THESE OR ANY OTHER
MATERIALS UNDER ACTUAL FIRE CONDITIONS

TABLE III

TYPICAL I.O.I. FOAM DATA*

| | <u>O.I.</u> | <u>I.O.I.</u> |
|----------------------------|-------------|---------------|
| REGULAR POLYETHER URETHANE | 16 | 15 |
| REGULAR POLYESTER URETHANE | 19 | 17 |
| F.R. POLYETHER URETHANE | 23 | 20 |
| ISOCYANURATE | 35 | 25 |
| HYPOL®-BASED | 38 | 28 |

* THESE VALUES ARE NOT INTENDED TO
REFLECT HAZARDS PRESENTED BY THESE
OR ANY OTHER MATERIALS UNDER ACTUAL
FIRE CONDITIONS.

FIGURE 1

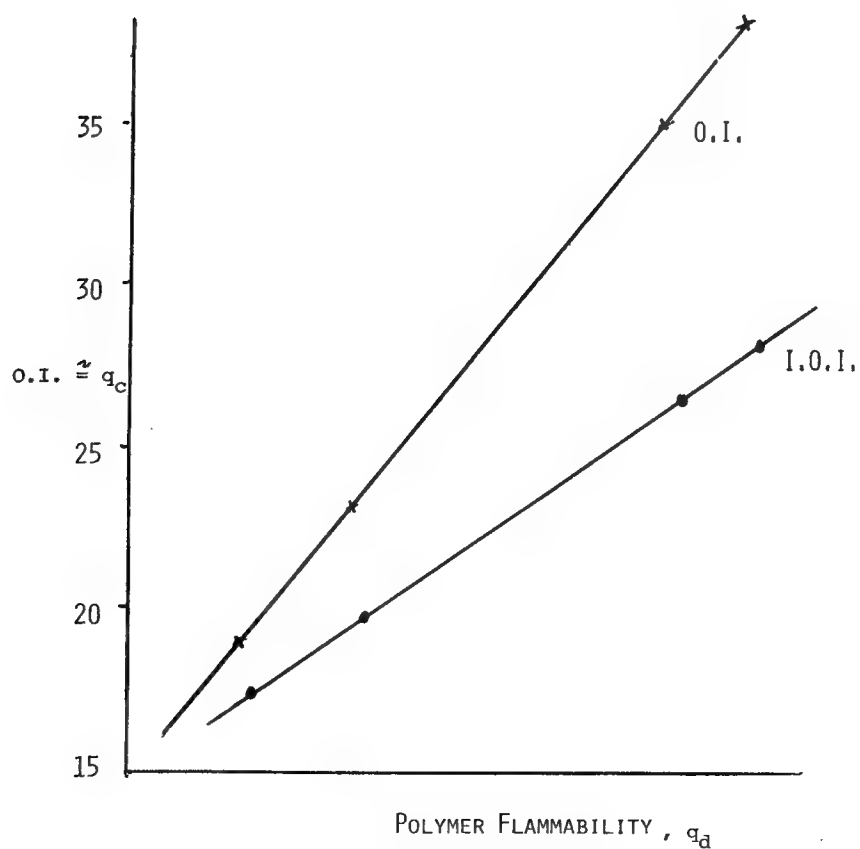
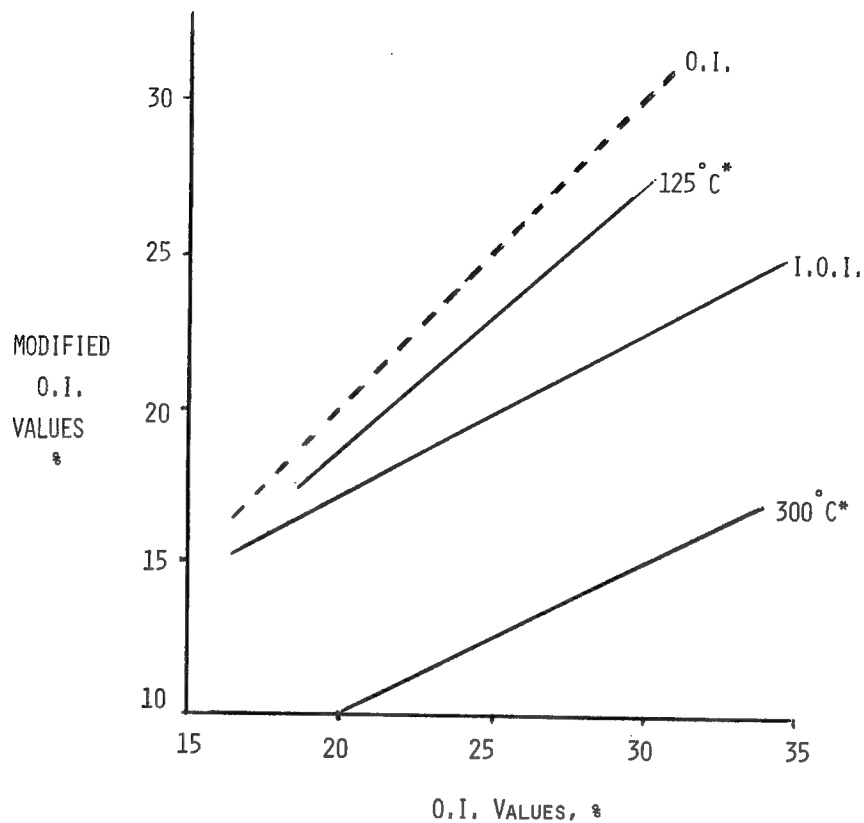
O.I. vs I.O.I. DATA

FIGURE 2

SLOPE CHANGES WITH MODIFIED O.I. PROCEDURES

* DiPIETRO, STEPNICZKA, J, FIRE & FLAMM. 2, 36 (1971)

TABLE IVO.I. VALUES* OF MATTRESS CORE MATERIALS

| <u>MATERIAL</u> | <u>O.I. (%)</u> |
|------------------------------|-----------------|
| POLYETHER URETHANE | 17 |
| POLYETHER URETHANE, F.R. | 24 |
| POLYESTER URETHANE, F.R. | 26 |
| NEOPRENE, BLACK | 36 |
| NEOPRENE, BUFF | 34 |
| NEOPRENE, 3/16" FIRE BARRIER | 34 |
| F.R. COMPOSITE FIBER BATTING | 28 |
| COTTON, WITH BORIC ACID | 34 |
| HYPOL® -BASED FOAM | 50 MINIMUM |

* THESE VALUES ARE NOT INTENDED TO REFLECT
HAZARDS PRESENTED BY THESE OR ANY OTHER
MATERIALS UNDER ACTUAL FIRE CONDITIONS.

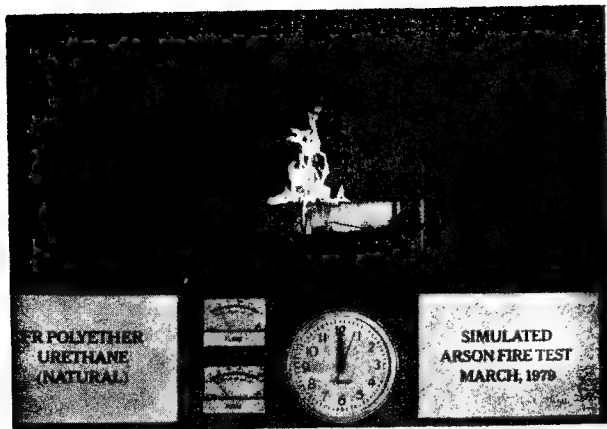


FIGURE 3



FIGURE 4

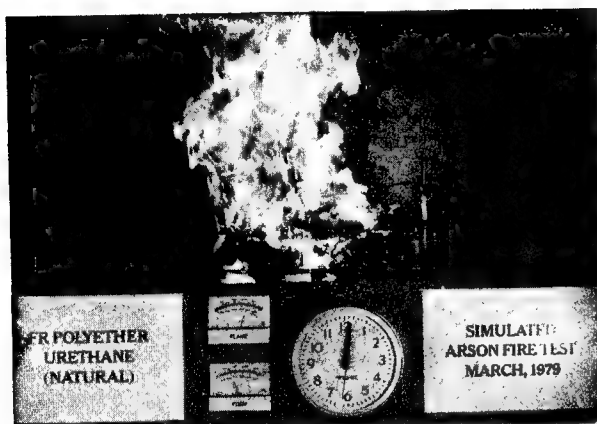


FIGURE 5

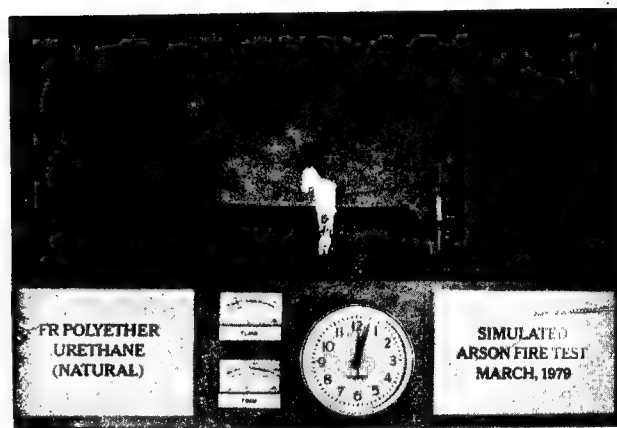


FIGURE 6

TABLE V

SUMMARY OF SPAT TESTS* (1)

| CORE MATERIAL | TIME (MIN) | | MAX FOAM TEMP (°C) | % DESTROYED |
|----------------------------------|------------|-------|-----------------------|----------------|
| | FLAMING | TOTAL | | |
| CONVENTIONAL POLYETHER URETHANE | 2 | 2 | 420 | 100 |
| F.R. POLYETHER URETHANE | 3 | 3 | 650 | 100 |
| F.R. POLYESTER URETHANE | 19 | 22 | 300 | 50 |
| NEOPRENE, BLACK | 4 | 45+ | 680 | 100 |
| NEOPRENE, BUFF | 16 | 45+ | 500 | > 90 |
| POLYURETHANE W/NEOPRENE OVERWRAP | 36 | 45+ | 460 | > 90 |
| F.R. COMPOSITE FIBER BATTING | 5 | 14 | 400 | 40 |
| COTTON, WITH BORIC ACID | 30 | 37+ | 500 | > 90 |
| HYPOL® -BASED FOAM | 21 | 33 | 60 | 20 |

* SPAT IS SIMULATED PRISON ARSON TEST.

(1) THESE VALUES ARE NOT INTENDED TO REFLECT HAZARDS PRESENTED BY THESE OR ANY OTHER MATERIALS IN ACTUAL FIRE CONDITIONS.



FIGURE 7



FIGURE 8



FIGURE 9

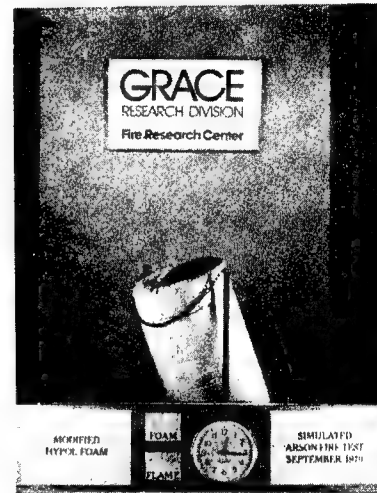


FIGURE 10

TABLE VI

SUMMARY OF MATTRESS ROLL-UP BURN TESTS*

| CORE MATERIAL | TIME (MIN) | | MAX FOAM TEMP. (°C) | % DESTROYED |
|----------------------------------|------------|-------|------------------------|----------------|
| | FLAMING | TOTAL | | |
| CONVENTIONAL POLYURETHANE | 5 | 5 | 500 | 100 |
| F.R. POLYETHER URETHANE | 5.5 | 5.5 | 500 | 100 |
| F.R. POLYESTER URETHANE | 9 | 13 | 700 | 100 |
| NEOPRENE, BLACK | 21.5 | 21.5 | 480 | 90 |
| NEOPRENE, BUFF | 42 | 60 | 600 | 70 |
| POLYURETHANE w/NEOPRENE OVERWRAP | 16+ | 16+ | 650 | > 90 |
| COTTON WITH BORIC ACID | 10 | 160+ | 600 | > 90 |
| HYPOL® -BASED FOAM | 5.5 | 12 | 120 | < 20 |

* THESE VALUES ARE NOT INTENDED TO REFLECT HAZARDS PRESENTED BY THESE OR ANY OTHER MATERIALS UNDER ACTUAL FIRE CONDITIONS.



FIGURE 11

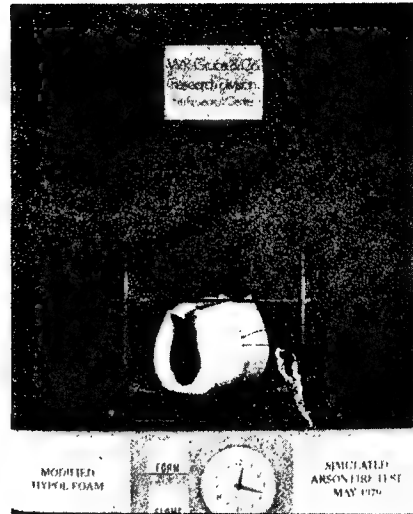


FIGURE 12

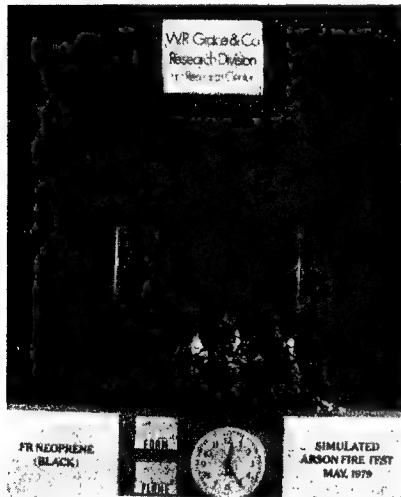


FIGURE 13



FIGURE 14

TABLE VII
SUMMARY OF TEAR DROP TESTS*

| CORE MATERIAL | TIME (MIN) | | MAX FOAM TEMP (°C) | % DESTROYED |
|-----------------------------------|------------|-------|-----------------------|----------------|
| | FLAMING | TOTAL | | |
| CONVENTIONAL POLYETHER URETHANE | 3.3 | 3.3 | 540 | 100 |
| F.R. POLYETHER URETHANE | 3.5 | 3.5 | 760 | 100 |
| F.R. POLYESTER URETHANE | 14 | 25 | 510 | > 90 |
| NEOPRENE, BLACK | 12 | 30 | 730 | > 90 |
| NEOPRENE, BUFF | 9 | 60+ | 510 | > 90 |
| URETHANE w/F.R. NEOPRENE OVERWRAP | 22 | 30 | 350 | > 90 |
| F.R. COMPOSITE FIBER BATTING | 12 | 37 | 590 | > 90 |
| COTTON WITH BORIC ACID | 30 | 60+ | 540 | > 90 |
| HYPOL® -BASED FOAM | 8 | 23 | 110 | < 20 |

* THESE VALUES ARE NOT INTENDED TO REFLECT HAZARDS PRESENTED BY THESE OR ANY OTHER MATERIALS UNDER ACTUAL FIRE CONDITIONS.

ALTERNATIVE FLAME RETARDANT FILLED SYSTEMS
FOR POLYESTER SPRAY-UP APPLICATIONS

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Introduction

During the past few years, there has been an increase in the use of plastics in the tub and shower market (Table I). Approximately one-quarter of the tubs and three-quarters of the showers are made of plastic materials (Table II). This market consists primarily of spray-up applications of flame-retardant, unsaturated polyester resin systems. There are about 130 companies in the U.S.A. manufacturing these tub and shower units using the spray-up technique.

Currently, alumina trihydrate (ATH) is used as both filler and fire retardant agent. This paper will discuss the use of two alternative systems which offer cost advantages without adversely affecting flame retardancy and which also enhance the physical appearance and properties of the finished product.

One system is based on the use of a calcium carbonate filler, designed specifically for polyester systems, as a partial replacement for the ATH plus a highly brominated resin concentrate in conjunction with the conventional system to obtain an estimated E 84 flame spread rating of about 100. The second system is designed to offer a cost advantage solely by replacing the ATH with up to 30% of the calcium carbonate, without adversely affecting the flame spread values. In addition to the cost advantage, the physical properties appear to be enhanced and a degree of opacity is imparted to the product.

Discussion

In this study, polyester systems were formulated based on a fifty per cent replacement of ATH by calcium carbonate and supplemented with a brominated resin and antimony trioxide. Formulations similar to these had previously been successful in SMC systems.¹ A formulation based totally on CaCO_3 , brominated resin, and Sb_2O_3 were also included to evaluate the performance of a system devoid of ATH. These formulations were selected after intensive laboratory studies (at Jim Walter Research Corp.) utilizing the Oxygen Index (ASTM D 2863), UL 94, and HLT-15 test procedures as screening tests on a variety of formulations. The best formulations as indicated by fire test performance, cost and viscosity effect were chosen.

The CaCO_3 used was Gama-Sperse FR-13, a filler designed specifically for use in polyester systems. The brominated resin was FR-1540, a dibromoneopentyl glycol-based unsaturated polyester resin designed to be blended with non-FR resin systems. The alumina trihydrate used was 336-LV, a product designed for use with low viscosity resins where parts are produced by the spray-up technique.

The primary test method employed was evaluation of flame spread using the JWRC 9-foot tunnel test procedure. This test determines the surface burning characteristics of a material under specific and controlled conditions. This 1/3-scale flame spread tunnel is used to predict potential performance of a material in an ASTM E 84 25-foot tunnel. The test method is based on the E 84 test procedure and on correlation studies conducted at JWRC using the 9-foot tunnel. This method is for product development purposes only and is not to be used for product certification or predicting performance under actual fire conditions.

The material to be tested is installed horizontally in the top of the tunnel chamber forming a rectangular duct. A sample size of 11-7/8" x 108" with a thickness up to 2-1/2" is required. Ignition of the lower sample surface is provided by an aspirated methane gas burner at one end of the sample. An induced draft provides controlled air movement through the tunnel chamber. The burner is ignited and the sample is tested for 10 minutes, with the flame

front distance being recorded at one-minute intervals. The maximum flame travel distance or the time it takes the flame front to travel 108" determines the flame spread rating for the material.

The test panels were prepared in-plant by a tub and shower stall manufacturer using standard spray-up production techniques and equipment. The procedure was such that the resin system, chopped glass strand, and catalyst were all applied simultaneously by means of a chopper/spray gun apparatus and rolled out by hand. This procedure was repeated several times until the desired thickness was obtained. The resultant panel was then cured.

In the production of tub and shower units, either a gel coat or an acrylic coating is applied to provide a smooth finished surface. Since there apparently are different standards set for gel coated and acrylic-based units, the test panels were evaluated without a surface treatment.

Since each set of panels was prepared by the spray-up method previously described, triplicate tests were run in the JWRC 9-foot tunnel to insure reproducibility of results. These test data are listed in Table III, and indicate that Sample #1 (control panel containing only ATH) and Sample #3 (50% replacement of ATH with CaCO_3 plus brominated resin and Sb_2O_3) have flame spread ratings which overlapped. The three panels tested of Sample #1 were erratic in burning behavior, whereas those of Sample #3 were consistent from panel to panel. Sample #2, containing more filler and less resin, yielded a slightly higher flame spread rating but was also very consistent from panel to panel. Sample #4, containing only CaCO_3 supplemented with the brominated resin and Sb_2O_3 , yielded an estimated flame spread rating of 141.

A Monsanto 2-foot tunnel test was also run on the panels, mainly to compare the data with that of the 9-foot tunnel and to evaluate the possibility of using this 2-foot tunnel for more accurate screening purposes.

In addition, certain physical tests were performed on the panels to determine whether the alternative systems varied in any way from the control panel. The

data, reported in Table IV, indicate that there is very little difference among the samples. The flexural strength and modulus are about equivalent for all samples tested. The Izod impact values obtained for all samples were also nearly the same.

As previously mentioned, the costs of the alternative systems are about equivalent to that of the control, and these suggested systems may be a good starting point for future investigations. Since Sb_2O_3 was used in all the alternative systems, further cost reduction can be realized by using any of the new lower priced nonantimony substitutes on the market.

A second series of panels was prepared based on the partial replacement of ATH with calcium carbonate. Preliminary studies indicated that this type of substitution would not significantly change the flame retardant properties of the system, but would definitely decrease the overall cost. Panels were prepared in the same manner as for the previous series. This time the ATH was replaced with 15, 20, 25 and 30% CaCO_3 and a higher glass loading was used. Again, the JWRC 9-foot tunnel was used to establish the flame spread ratings and the test results are listed in Table V. Only very slight increases in the flame spread ratings were indicated as the replacement level increased.

Just as significant was the increase in the physical properties which resulted from the addition of the CaCO_3 . As shown in Table VI, the flexural strength increased in all cases. There were also indications that the Izod impact strength improved.

A third advantage derived from the use of the CaCO_3 was the opacity which was imparted to the panels. Usually pigments, such as titanium dioxide, are added to the resin system to impart opacity for aesthetic reasons. Thus, the use of CaCO_3 eliminates the extra cost of using a pigment.

The E-84, 25-foot tunnel results were very encouraging. There is little or no difference between the flame spread ratings of panels made with 100% ATH and a 20% replacement of the filler with CaCO_3 .

The panel with the brominated resin and a 50/50 mixture of ATH and CaCO_3 is the only one that achieves a Class II rating with a flame spread of 70, while being cost-competitive with the other formulations.

This opens up new opportunities in the polyester spray-up field to insure better flame retardancy at no extra cost to financial or physical considerations.

Summary

Several alternative systems for polyester spray-up applications have been suggested which offer a cost advantage without affecting flame retardancy. In addition, added benefits such as improved physical properties and appearance may be realized.

Acknowledgements

We gratefully acknowledge the cooperation of John Tinney and National Florida Fiberglass Corp. for the use of their facilities and equipment in the preparation of the test panels.

We would also like to thank both William Miller of the Georgia Marble Company and Robert Cramer of The Dow Chemical Company for their support of this project.

We also appreciate the efforts of G. Griswold and T. Hreshko of Jim Walter Research Corp.

Materials

Gama-Sperse FR-13 - Georgia Marble Company, CaCO_3 designed specifically for polyester systems

FR-1540 Dow Chemical Company, dibromoneopentyl glycol-based unsaturated polyester resin designed to be blended with non-FR resin systems

ATH Solem Industries, 336-LV

AZS Resin AZ Products, polyester spray-up resin

Fiberglass Certain-Teed Corp., chopped gun roving

Sb_2O_3 NL Industries, Red Star antimony trioxide

Note: Cost estimates based on standard published prices for truckload quantities.

TABLE I

TUB AND SHOWER STALL MARKET, 1972 TO 1977BATHTUBS (1,000'S OF UNITS)

| | <u>ALL MATERIALS</u> | <u>PLASTICS</u> | <u>PLASTICS SHARE (%)</u> |
|------|--------------------------|-----------------|-------------------------------|
| 1972 | 3,647 | 509 | 14 |
| 1973 | 3,576 | 573 | 16 |
| 1974 | 2,625 | 496 | 19 |
| 1975 | 2,022 | 398 | 20 |
| 1976 | 2,916 | 586 | 20 |
| 1977 | 2,732 | 713 | 26 |

SHOWER STALLS (1,000'S OF UNITS)

| | <u>ALL MATERIALS</u> | <u>PLASTICS</u> | <u>PLASTICS SHARE (%)</u> |
|------|--------------------------|-----------------|-------------------------------|
| 1972 | 406 | 260 | 64 |
| 1973 | 388 | 262 | 68 |
| 1974 | 386 | 260 | 67 |
| 1975 | 387 | 232 | 60 |
| 1976 | 511 | 354 | 69 |
| 1977 | 554 | 398 | 72 |

SOURCE: REFERENCE 2

References

1. Cost Effective Ignition Resistant Filled Systems For Polyester Moldings, C. J. del Valle, Dow Chemical, 32nd SPI Conference, 1978.
2. Plastics in Building Construction, Vol. III, No. 1, Oct. 1978, p. 5.

TABLE II

TUBS AND SHOWER MARKET (1977)

| <u>TUBS</u> | <u>UNITS</u> | <u>\$</u> |
|--------------------------|------------------|---------------|
| TOTAL | 2,732,000 | 243,500,000 |
| CAST IRON | 826,300 | 103,100,000 |
| ENAMEL-STEEL | 1,192,700 | 55,500,000 |
| PLASTIC (26%) | 713,000 | 85,000,000 |
| <u>SHOWER STALLS</u> | <u>UNITS</u> | <u>\$</u> |
| TOTAL | 554,000 | 67,300,000 |
| STEEL | 156,000 | 17,500,000 |
| PLASTIC (72%) | 398,000 | 49,800,000 |
| TOTAL PLASTIC MARKET | <u>UNITS</u> | <u>\$</u> |
| | 1,111,000 | 134,800,000 |

SOURCE: DEPARTMENT OF COMMERCE DATA

TABLE III

BURNING TESTS

ON FRP PANELS CONTAINING CaCO_3 , ATH, BROMINE AND Sb_2O_3

| <u>SAMPLE #</u> | <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> |
|-------------------------------|----------|----------|----------|----------|
| RESIN (LBS) | 55.0 | 43.4 | 48.4 | 43.0 |
| ATH (LBS) | 45.0 | 25.6 | 22.5 | - |
| FR-1540 (LBS) | - | 4.0 | 5.0 | 9.9 |
| GAMA-SPERSE FR-13 (LBS) | - | 25.6 | 22.5 | 44.6 |
| Sb_2O_3 (LBS) | - | 1.3 | 1.6 | 2.5 |
| FIBERGLASS CONTENT (%) | 11.7 | 12.0 | 11.0 | 11.4 |

TEST RESULTS

A) JWRC 9-FT TUNNEL (1)

| | | | | |
|---------------------------------|---------|---------|---------|---------|
| (AVE. FLAME SPREAD/E 84 METHOD) | 105 ± 9 | 128 ± 1 | 114 ± 1 | 141 ± 0 |
|---------------------------------|---------|---------|---------|---------|

B) MONSANTO 2-FT TUNNEL (2)

| | | | | |
|----------------------|----|----------------------------|----------------------------|----------------------------|
| (FLAME TRAVEL - IN.) | 20 | OUT OF TUNNEL (165 SEC) | OUT OF TUNNEL (150 SEC) | OUT OF TUNNEL (113 SEC) |
|----------------------|----|----------------------------|----------------------------|----------------------------|

(1) THIS METHOD IS FOR PRODUCT DEVELOPMENT PURPOSES ONLY AND IS NOT TO BE USED FOR PRODUCT CERTIFICATION OR PREDICTING PERFORMANCE UNDER ACTUAL FIRE CONDITIONS.

(2) THIS IS PRIMARILY A SCREENING TEST AND IS NOT BE USED TO PREDICT PERFORMANCE UNDER ACTUAL FIRE CONDITIONS.

TABLE IV

PHYSICAL TESTS ON FRP PANELS
CONTAINING CaCO_3 , ATH, BROMINE, AND Sb_2O_3

| <u>SAMPLE #</u> | <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> |
|-------------------------------|----------|----------|----------|----------|
| RESIN (LBS) | 55.0 | 43.4 | 48.4 | 43.0 |
| ATH (LBS) | 45.0 | 25.6 | 22.5 | - |
| FR-1540 (LBS) | - | 4.0 | 5.0 | 9.9 |
| GAMA-SPERSE FR-13 (LBS) | - | 25.6 | 22.5 | 44.6 |
| Sb_2O_3 (LBS) | - | 1.3 | 1.6 | 2.5 |
| FIBERGLASS CONTENT (%) | 11.7 | 12.0 | 11.0 | 11.4 |
| - - - - - | | | | |

TEST RESULTS

| | | | | |
|----------------------------------|--------|--------|--------|--------|
| FLEXURAL STRENGTH (PSI) | 12,300 | 11,600 | 12,200 | 12,000 |
| (ASTM D 790) (MPA) | 85 | 80 | 84 | 83 |
| FLEXURAL MODULUS (PSI x 10^6) | 1.10 | 1.03 | 1.07 | 1.09 |
| (ASTM D 790) (GPA) | 7.6 | 7.1 | 7.4 | 7.5 |
| IZOD IMPACT, NOTCHED (FT.LB/IN) | 4.5 | 4.7 | 3.8 | 4.4 |
| (ASTM D 256) (J/cm) | 2.4 | 2.5 | 2.0 | 2.3 |
| BARCOL HARDNESS | 55-60 | 57-60 | 58-62 | 59-62 |
| (ASTM D 2583) | | | | |

TABLE V

BURNING TESTS

REPLACEMENT OF ATH WITH GAMA-SPERSE FR-13

| <u>SAMPLE #</u> | <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> | <u>5</u> |
|---------------------------------|----------|----------|----------|-------------------------|-------------------------|
| RESIN (LBS) | 100 | 100 | 100 | 100 | 100 |
| ATH (LBS) | 100 | 85 | 80 | 75 | 70 |
| GAMA-SPERSE FR-13 (LBS) | - | 15 | 20 | 25 | 30 |
| FIBERGLASS CONTENT (%) | 18.5 | 18.7 | 15.4 | 19.4 | 18.4 |
| ----- | | | | | |
| <u>TEST RESULTS</u> | | | | | |
| A) 9-FOOT TUNNEL (1) | | | | | |
| (AVE. FLAME SPREAD/E 84 METHOD) | 93±3 | 100±7 | 108±5 | 120±9 | 117±2 |
| B) MONSANTO 2-FOOT TUNNEL (2) | | | | | |
| (FLAME TRAVEL - INCHES) | 20 | 20 | 20 | OUT OF TUNNEL (165 SEC) | OUT OF TUNNEL (145 SEC) |
| ----- | | | | | |
| COST (3) - \$/100 LBS. | 26.75 | 26.04 | 25.80 | 25.57 | 25.33 |

- (1) THIS METHOD IS FOR PRODUCT DEVELOPMENT PURPOSES ONLY AND IS NOT TO BE USED FOR PRODUCT CERTIFICATION OR PREDICTING PERFORMANCE UNDER ACTUAL FIRE CONDITIONS.
- (2) THIS IS PRIMARILY A SCREENING TEST AND IS NOT BE BE USED TO PRE-DICT PERFORMANCE UNDER ACTUAL FIRE CONDITIONS.
- (3) EXCLUDES PRICE OF FIBERGLASS AND CATALYST.

TABLE VI

PHYSICAL TESTS

FRP PANELS CONTAINING CaCO_3 REPLACEMENT OF ATH

| <u>SAMPLE #</u> | 1 | 2 | 3 | 4 | 5 |
|----------------------------------|--------|--------|--------|--------|--------|
| RESIN (LBS.) | 100 | 100 | 100 | 100 | 100 |
| ATH (LBS.) | 100 | 85 | 80 | 75 | 70 |
| GAMA-SPERSE FR-13 (LBS) | | 15 | 20 | 25 | 30 |
| FIBERGLASS CONTENT (%) | 18.5 | 18.7 | 15.4 | 19.4 | 18.4 |
| ----- | | | | | |
| <u>TEST RESULTS</u> | | | | | |
| FLEXURAL STRENGTH (PSI) | 12,600 | 14,500 | 13,000 | 13,800 | 15,200 |
| (ASTM D 790) (MPA) | 87 | 100 | 90 | 95 | 105 |
| FLEXURAL MODULUS (PSI x 10^6) | 1.13 | 1.29 | 1.16 | 1.23 | 1.36 |
| (ASTM D 790) (GPA) | 7.8 | 8.9 | 8.0 | 8.5 | 9.4 |
| IZOD IMPACT, NOTCH (FT. LB/IN) | 3.8 | 4.5 | 3.8 | 3.8 | 5.1 |
| (ASTM D 256) (J/cm) | 2.0 | 2.4 | 2.0 | 2.0 | 2.7 |
| BARCOL HARDNESS | | | | | |
| (ASTM D 2583) | 55-60 | 55-60 | 55-60 | 55-60 | 55-60 |

PHYSICAL TEST RESULTS

Panel

| <u>FORMULATION (LBS.)</u> | <u>#1</u> | <u>#2</u> | <u>#3</u> | <u>#4</u> |
|--------------------------------|-----------|-----------|-----------|-----------|
| Resin | 100 | 100 | 100 | 96.8 |
| ATH | 100 | 80 | 70 | 45.0 |
| Gama-Sperse FR-13 | - | 20 | 30 | 45.0 |
| FR-1540 | - | - | - | 10.0 |
| Sb ₂ O ₃ | - | - | - | 3.2 |
| % Fiberglass | 13.7 | 14.3 | 11.3 | 14.4 |

TEST RESULTS

| | | | | |
|---|--------|--------|--------|--------|
| Izod Impact, Notched (ft.lbs./inch) | 5.3 | 5.6 | 6.3 | 5.4 |
| (ASTM D 256) (J/Cm) | 2.8 | 3.0 | 3.4 | 2.9 |
| Flexural Strength (psi) | 14,350 | 15,000 | 13,140 | 15,570 |
| ASTM D 790 (MPa) | 98.9 | 103.4 | 90.6 | 107.4 |
| Flexural Modulus (psi x 10 ⁶) | 0.93 | 0.97 | 0.95 | 0.95 |
| ASTM D 790 (GPa) | 6.4 | 6.7 | 6.6 | 6.6 |
| Shear Strength (psi) | 2,090 | 2,400 | 1,800 | 2,300 |
| (ASTM D-2344) (MPa) | 14.4 | 16.5 | 12.4 | 15.9 |

TUNNEL TEST RESULTS

| | Panel | | | |
|--------------------------------|-------|------|------|------|
| | #1 | #2 | #3 | #4 |
| <u>FORMULATION (LBS.)</u> | | | | |
| Resin | 100 | 100 | 100 | 96.8 |
| ATH | 100 | 80 | 70 | 45.0 |
| Gama-Sperse FR-13 | - | 20 | 30 | 45.0 |
| FR-1540 | - | - | - | 10.0 |
| Sb ₂ O ₃ | - | - | - | 3.2 |
| % Fiberglass | 13.7 | 14.3 | 11.3 | 14.4 |
| | | | | 240 |

| | | | | |
|---|----------------|----------------|-----------------|-----------------|
| <u>TEST RESULTS</u> | | | | |
| E-84 25-Foot Tunnel <u>1</u> | 90 (1975 Std.) | 95 (1975 Std.) | 100 (1975 Std.) | 70 (1975 Std.) |
| Flame Spread Index <u>7</u> | 60 (1977 Std.) | 70 (1977 Std.) | 75 (1977a Std.) | 50 (1977a Std.) |
| ----- | | | | |
| JWRC 9-Ft. Tunnel (Flame Spread Index/ E-84 Method (1975 Std.)) | Not Tested | 92 | 120 | 92 |

A Review of Flame Retardant
Unsaturated Polyester Resin Technology
Using Firemaster® PHT4®,
Tetrabromophthalic Anhydride

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*Firemaster and PHT4 are registered trademarks of Velsicol Chemical Corporation.

Abstract

The use of tetrabromophthalic anhydride (TBPA) as a reactive intermediate in the production of flame retardant unsaturated polyester resins will be discussed. An outline of a typical single stage fusion cook will be presented with special emphasis on the neutralization step. Formulation versatility will be demonstrated through the use of various co-acids and glycols and the range of bromine content that can be achieved. Specific formulations will be presented which demonstrate TBPA's utility in marine and chemical resistant resins. Data will be presented on the smoke evolution and off-gas toxicity of a TBPA resin as compared to a general purpose resin.

Tetrabromophthalic anhydride (TBPA), Firemaster PHT4, has long been an important reactive flame retardant intermediate for unsaturated polyester resins. Its high bromine content (68.9% Br) allows formulation versatility while maintaining a high degree of flame retardancy. Synergists, like antimony trioxide, are usually incorporated into the TBPA polyester resin, but may not be needed to obtain the desired level of flame retardancy.

Preparation of TBPA Polyester Resins

TBPA polyester resins are prepared using conventional polyesterification techniques. However, two precautions must be taken to insure consistently good resins. In the manufacture of Firemaster PHT4, a trace amount of acid (reported in terms of sulfuric acid) remains in the product. To be assured of consistently high quality resins, the acid must be properly neutralized before reactants are heated. The residual acid may be neutralized with anhydrous sodium acetate, diethanolamine, or triethanolamine.

For example, if the TBPA contains 0.20% acid (as sulfuric), then 0.52 pounds of anhydrous sodium acetate would be needed for every 100 pounds of TBPA used. Failure to neutralize the acid results in cyclization and loss of some of the glycol into the distillate. This adversely affects the resin color and stability. The other precaution is that a recommended polyesterification temperature of 185°C (265°F) should not be exceeded.⁽¹⁾ As the temperature of esterification is increased beyond this temperature, undesirable decarboxylation becomes significant.

In the past, certain halogen containing intermediates have been responsible for corrosion of reaction vessels used in polyester resin technology. However, a properly neutralized and prepared TBPA resin will not adversely affect stainless steel (SS) reaction vessels. The metal ion content of TBPA resins prepared in 316 SS, 304 SS, and glass reaction vessels is similar among all three vessels with the iron content at less than 4.1 ppm, the chromium content at less than 2.1 ppm, and the nickel content at less than 1.3 ppm. When TBPA is added to the polyesterification reaction mass at elevated temperatures, a significant increase in the metal ion content of the resulting resin occurs which can lead to corrosion of the reaction vessel.

TBPA resin cooking times are comparable to that of a general purpose resin and at times may be shorter. An average of 6 to 7.5 hours reaction time is normal for a TBPA resin laboratory cook. A molecular weight of 1,900 to 2,000 is achieved with an alkyd of acid number approximately equal to 30. A slightly higher molecular weight can be obtained by cooking to a lower acid number.

The Gardner color of a TBPA resin diluted to 35% styrene is 2-4, with the range dependent upon the type of neutralizing agent employed. In general, when sodium acetate is used, the Gardner color will be 2-3, the viscosity will be low, and there will be a slight, filterable precipitate of sodium sulfate causing the resin to be slightly hazy. If diethanolamine is used to neutralize TBPA, the Gardner color will be 3-4, the viscosity will be slightly higher, and the resin will be clear.⁽¹⁾

Characteristics of Cured TBPA Resins

The mechanical properties of the TBPA resin laminate and casting are typical of flame retardant resins. The heat deflection temperature (HDT), run according to the ASTM D648-72 test method, is about 105°C and can be increased by increasing the unsaturated acid to saturated acid ratio. Of course, longer chain glycols like diethylene glycol or 1,3 propanediol will decrease the HDT. The flexural strength and modulus of the TBPA resins are comparable to many commercial resins. Incorporating 25 mole percent of a co-glycol in a TBPA resin that is based on ethylene glycol does not adversely affect the flexural strength and modulus.⁽²⁾

TBPA polyester resins can be formulated to impart a high degree of flame retardancy. At this point, it should be stated that any reference to test ratings are presented for comparative purposes and are relevant only to conditions of the specific test mentioned. Such ratings are not to be interpreted as applying to conditions of a real fire situation. The oxygen index (O.I.), run according to the ASTM D2863 test method, of a 20% bromine TBPA resin is 36.0%. This can be increased dramatically by the use of the synergist antimony trioxide. Other synergists like triethyl phosphate or zinc borate can be employed also. The choice of glycol has a major influence on the flame retardancy secured with halogenated polyesters. The effect of the glycol on flammability was measured by O.I., and ethylene glycol showed a substantial increase in O.I. value over propylene glycol at an equal percent bromine. Other glycols that reduce the flame retardancy of a resin are neopentyl glycol and cyclohexanedimethanol.

Smoke Evolution and Off-Gas Toxicity

While the smoke evolution of a flame retardant polyester resin is somewhat higher than of a general purpose resin, the off-gas toxicity does not show a similar trend. Using an incapacitation-type test on rats for inhalation toxicity, it has been found that a TBPA polyester resin laminate creates no higher levels of carbon monoxide and carbon dioxide during combustion than a general purpose resin laminate.

Liquid Blendable Flame Retardants

TBPA polyester resins can be formulated to contain a high level of bromine if TBPA and maleic anhydride, in an 1:1 molar ratio, are used as the only diacids. When the styrene level is lowered to 25%, the resulting bromine level is about 35%. Resins of this nature are generally too high in bromine and too viscous for use alone. These high bromine containing unsaturated polyester resins are used as liquid blendable flame retardants. The resin can be incorporated into non-halogenated polyester resins to impart some flame retardancy or it can be added to already halogenated resins to enhance the flame retardancy. Using a polyester resin as a flame retardant additive combines the advantages of both. Since the bromine is chemically bonded to the backbone of the polymer, once the resin system is crosslinked, the bromine will not leach out of the system. The liquid blendable flame retardant can be added to the base resin at a variety of levels depending upon the degree of flame retardancy desired. The liquid blendable flame retardant is easily mixed into another polyester resin forming a clear resin system with no problem of separation or settling.

Cooking a polyester resin where 25 mole percent of the alkyd is TBPA requires the use of a mixed glycol system. To avoid the loss of mobility during the initial stage of the polyesterification, a mixture of 2/3 ethylene glycol and 1/3 diethylene glycol is necessary. Once the half-ester is totally formed, the reaction proceeds rapidly and smoothly to completion.

Marine TBPA Resins

A specialty application for unsaturated polyester resins is in the naval applications area. The U.S. Navy and later the U.S. Coast Guard adopted two military specifications covering the flame resistance and physical properties of low pressure laminating polyester resins, MIL-R-21607C and MIL-R-7575C. A 16% to 17% bromine TBPA resin passes the Grade 1 specification of MIL-R-21607C (a spark-coil type flammability test) initially and after one year's outdoor weathering. These same resins also meet the Grade A requirements of MIL-R-7575C, which includes flexural strength and modulus tested wet, flexural strength and modulus tested at 70°C after exposure at 70°C for one-half hour, and flexural strength and modulus tested after one year outdoor weathering.^(2,3)

Corrosion Resistant TBPA Resins

Another specialty area for polyester resins is applications that require chemical resistance as well as flame retardancy. Chemical resistant TBPA resin laminates along with two commercial resin laminates used as controls, Dion[®] 6693 and Hetron[®] 197-3, were tested at elevated temperatures in various corrosion media according to ASTM C581 test method. After one year exposure, TBPA resins containing a glycol mix of 50% ethylene glycol and 50% neopentyl glycol retained flexural properties

equal to or better than the two commercial resins. TBPA resins can be formulated to achieve corrosion resistance that is acceptable for applications in the construction industry.⁽⁴⁾

Summary

TBPA can be effectively used in unsaturated polyester resins to impart various degrees of flame retardancy. TBPA resins can be used in specialty areas where flame retardancy as well as specific properties, like chemical resistance, are needed. This versatility of TBPA along with its high bromine content allows it to be used in a wide range of flame retardant applications.

Trademarks

- Firemaster - Registered trademark of Velsicol Chemical Corporation.
- PHT4 - Registered trademark of Velsicol Chemical Corporation.
- Dion - Registered trademark of Koppers Company, Incorporated.
- Hetron - Registered trademark of Ashland Chemical Corporation.

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MASS BURNING RATE AND RELATIVE FIRE HAZARD OF
POLYMERS AND OTHER FUELS

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I. Introduction

The increased usage of plastics during the present decade has been accompanied by an increased concern about the fire hazards associated with the widespread utilization of these materials. The ease of processability, cost, and tensile strength are among the factors which led to the widespread use of polymers in the construction, transportation, and electronics industries, among others.

The fire hazards associated with polymers include ease of ignition, mass burning rates, total heat release and production of potentially toxic gases and smokes. The latter hazards are amenable to standard laboratory testing techniques, and to a large measure, determine the toxic hazards associated with the smoke and gaseous combustion products.

Once a materials is ignited, the complex interactions between the exothermic flame front and the endothermic material surface determine the rate at which the material burns and generates heat. A systematic study of the burning rates of various materials under controlled conditions of oxygen content and heat flux will permit a relative ranking of the fire hazards of the materials to be ascertained. The ranking will indicate only the steady-rate burning properties of the materials, and will not indicate the ease of ignition.

The Mass Burning Rate techniques are described by Tewarson and Pion¹⁻³ is one of the newer test methods used to evaluate burning rates for solid and liquied fuels. The fuels are burned in a pool-like configuration precluding effects due to sample geometry or shape. The side walls of the sample holder confine the sample to the holder and prevent it from flowing away from the flame and extinguishing itself. External radiant panels can be used to augment the heat flux striking the fuel surface, creating conditions which can only be found in large fires. The external heat source makes it possible to study burning rates of the materials over a wide range of conditions, from pyrolysis to full scale flames. The technique also allows one to study the burning behavior of the fuels under a variety of oxygen levels in a manner similar to that of the Limiting Oxygen Index technique.⁴

It has been shown that energy transfer is a significant factor affecting the burning behavior and flame spread rate of many solid and liquid fuels.⁵⁻⁸

Tewarson and Pion have shown that the Spalding Mass Transfer number, B ,⁹ of a fuel can be correlated to its mass burning rate as determined by the technique described by them.¹⁻³

It has more recently been shown that the Mass Burning Rate technique can be correlated to the Limiting Oxygen Index of the fuel.¹⁰ Additionally, the technique can be shown to reveal a definite relationship between the B number and the "apparent" heat of gassification of many fuels. The correlation holds for liquids as well as solids, for aromatics, as well as aliphatic fuels, and for halogen or nitrogen-containing fuels, as well as for hydrocarbons.

II. Experimental Apparatus and Procedure

The apparatus used in this study has been previously reported¹⁰⁻¹¹ and is shown in Figure 1. A total of 138 different solid and liquid fuels have been studied. Of those materials studied, it was possible to correlate the burning rates to the B number for only 100 fuels. This was due to the unavailability of thermochemical data necessary to calculate the B number, as will be described in the next section.

Solid fuels were machined into discs of diameter 8-15 cm. Disc thicknesses were 1.8 to 5 cm. The solid fuels were mounted in circular aluminum pans whose area was slightly larger than that of the sample. The samples were placed on the load cell supported platform. The gaseous N_2/O_2 atmosphere flowing around the sample was fixed by Rotameters prior to ignition of the samples. The samples were ignited by a methane/air flame to initiate each study. Steady-state weight losses were determined for each fuel at each of several oxygen levels.

The fuels were also burned in the presence of external heat fluxes from the calibrated radiant panels shown in Figure 1.

Liquid fuels were burned in pyrex dishes ranging in diameter from 10 to 30 cm. and in depth from 2.5 to 7 cm.

The steady-state mass burning rate (gm/cm^2 sec) was obtained by dividing the steady-state weight loss (gm/sec) by the initial sample area (cm^2). A series of mass burning rates is thus obtained at different mole fractions of oxygen at several heat flux levels (cal/cm^2 sec) for each of the fuels subjected to the procedure.

III. Combustion Theory and Background

The theoretical basis for the Mass Burning Rate technique and procedure has been described elsewhere.¹⁻² The pertinence to the present study has also been reported.¹⁰⁻¹¹

Spalding shows the following relationship to exist between the thermochemical properties and the mass transfer number B, for a burning fuel.

$$B = \left[\frac{M_{O_2} \cdot H_c - C_p (T_s - T_a)}{r} \right] / L_g \quad (1)$$

where;

M_{O_2} = mass fraction of oxygen in the combustion environment

r = stoichiometric oxygen/fuel mass ratio

H_c = heat of combustion of the fuel (cal/gm)

C_p = specific heat of air (cal/gm °C)

T_s = surface temperature of the burning fuel (°C)

T_a = ambient air temperature (°C)

Tewarson and Pion¹⁻³ have shown that the term in the denominator can be obtained from the Mass Burning Rate technique, as well as from conventional calorimetry. They have given the term L_g , the name "apparent" heat of gasification with particular reference to polymeric systems where volatilization, depolymerization, and in many cases decomposition all occur at the same time at the burning surface. We will, henceforth, refer to L_g as the "apparent" heat of asification as many of the processes inherent in the definition also occur during the pyrolysis of the other fuels considered in this report. The theoretical arguments reported herein are taken from Tewarson and Pion, except where noted.

Tewarson gives the following expression for the relationship between the mass burning rate, \dot{m}'' (gm/cm²sec), and the Spalding mass transfer number B, in the presence of an external source of radiation, as would surround an element of fuel in a large fire where other elements are burning, and thusly contributing radiation to the element under consideration.

$$\dot{m}'' = C \cdot B^n (1-E)^{-n} = c B^n (1 + nE + n(n+1) \frac{E^2}{2I} + \dots) \quad (2)$$

where;

\dot{m}'' = mass burning rate (gm/cm² sec)

C = a constant

E = Net additional combustion due to radiation (dimensionless)

n = a constant

At the "ideal" mass burning rate, where the external radiant heat flux just balances the heat losses from the fuel, $E \sim 0$ and equation (2) reduces to

$$\dot{m}''_{\text{ideal}} \sim \frac{CB^n}{C} \left(\frac{M_{O_2} \cdot Hc}{r \cdot Lg} \right)^n \quad (3)$$

since the second term in the numerator of equation (1) is much less than the first term, and can be ignored. For the present, the mass transfer number, B , will be defined as

$$B = \frac{M_{O_2} \cdot Hc}{r \cdot Lg} \quad (3a)$$

and as such, will be used in all further discussions.

The purpose of this study was to determine the values for the constants c and n in equation (3), for various types of fuels. Regression analysis of the data should reveal the validity of the equation for given fuel types and structures.

The Limiting Oxygen Index (LOI) determines the minimum oxygen concentration in an O_2/N_2 atmosphere which will sustain combustion. In the terminology of the present study, the LOI is the oxygen content at which the heat flux from the flame just exceeds the heat losses from the burning sample surface. That is

$$\dot{Q}''_t = \dot{Q}''_l \quad (4)$$

where;

\dot{Q}''_t = heat flux from the flame to the fuel surface
(cal/cm² sec)

\dot{Q}''_l = heat flux lost from the burning surface (cal/cm² sec)

The heat flux from the flame has been assumed to obey the relation

$$\dot{Q}''_t = \xi \cdot N_{O_2}^\alpha \quad (5)$$

where;

ξ and α are constant and N_{O_2} = mole fraction O_2 .

It has been shown that over a wide range of oxygen levels
 $\alpha = 1.1^{-3,5}, 10^{-12}$

Substituting the RHS of equation (5) into equation (4) and rearranging, one obtains

$$N_{O_2} = \frac{\dot{Q}_I''}{\xi} = LOI_{theo} \quad (6)$$

for the LOI value of the fuel burned in the Mass Burning Rate apparatus.¹⁰ The agreement between the "theoretical" LOI calculated from equation (6) and experimental values is quite good. Most materials do not show an area affect on the LOI. For those that do, the value is in the direction indicated by the "theoretical" value calculated from equation (6).

Equation (3a) can be written in the form

$$B = AL_g^n \quad (7)$$

where;

$$A = \frac{M_{O_2} \cdot H_c}{r} = \text{a constant?}$$

$n = \text{constant}$ (in 3a, it is -1)

Since the values of L_g can be determined by the Mass Burning Rate technique, the author explored the relationship between B and L_g . As will be shown later, when these two values for the different fuels were plotted linearly, a parabolic curve resulted. This suggested a power fit might be an appropriate relationship. Such is the case, as will be shown.

IV. Experimental Results

Table 1 lists the combustion data obtained for 100 materials for which it was possible to calculate a B number from equation (3a). Column 2 lists the values of ξ , the coupling constant which determines the heat flux from the flame at $N_{O_2} = 1.00$ (pure oxygen). Columns 3 and 4 list the heat flux \dot{Q}_2 from the flame to the fuel surface and the heat flux losses from the surface at $N_{O_2} = 0.21$, respectively (ambient atmosphere). The "apparent" \dot{Q}_2 heat of gasification (L_g) is shown in column 5. It was calculated from thermodynamic tables for the liquid fuel. The L_g values for all solid fuels were derived from mass burning rate studies or from differential scanning calorimetry.

Column 6 lists the "ideal" mass burning rates, \dot{M}^{ideal} . These values were derived from the experimental ideal burning rate studies carried out under the influence of external heat fluxes supplied by the radiant panels. The "ideal" mass burning rate is defined as the burning rate in an ambient atmosphere when the external heat flux (\dot{Q}'') equals the heat flux loss from the sample surface (\dot{Q}_1''). At this condition, all of the heat flux from the flame (\dot{Q}_t'') goes into degrading and volatilizing the fuel to sustain the flame.

Column 7 lists the literature values for the heat of combustion of the fuels. The Spalding mass transfer number, B , is listed in column 8. It was calculated from equation (3a) with M_{O_2} equal to 0.232 for ambient conditions.

The "theoretical" LOI values are listed in column 9. They were obtained through use of equation (6) and the ξ and \dot{Q}_1'' values found in columns 2 and 4, respectively.

The A values of equation (7) are listed in column 10. These values are intrinsic to each fuel and are fundamental properties of that fuel. They are the heat input term of the transfer number B as defined by equation (3a).

The materials listed in Table 1 may be divided into several categories. For purposes of discussion, they will be divided as follows:

- (a) Aromatic fuels—all fuels, both liquid and solid which are characterized by a benzene ring in the molecule or monomeric unit.
- (b) Aromatic polymer—polymer containing a benzene ring in the monomer unit, i.e. polystyrene, SAN, polycarbonate, polysulfone.
- (c) Wood—natural woods without fillers.
- (d) Aliphatic fuels—all fuels not containing a benzene ring, whether solid polymer, such as polyethylene PMMA, PVC or Saran, or liquids.

A Aromatic Fuels

The aromatic fuels tend to have large values for ξ and consequently, also for \dot{Q}_t'' . The materials are characterized by the presence of large amounts of soot in the flame. Aromatic liquids have the largest B numbers of those materials studied. They are larger than those for the

aromatic polymers. This is due to the smaller values of L_g in the denominator of equation (3a), not the H_c values which are equivalent for liquid and solid aromatic fuels.

Bromobenzene was the only aromatic liquid studied that did not burn at a N_{O_2} of 0.21 or less. Consequently, its heat flux \dot{Q}_2 losses from the liquid surface (\dot{Q}_1'') was larger than its heat flux input from the flame at ambient condition (\dot{Q}_t''). Also, its LOI then is greater than 0.21. Materials which will not burn at $N_{O_2} = 0.21$ are characterized by having \dot{Q}_1'' values larger than \dot{Q}_2 the \dot{Q}_t'' values.

B Aromatic Polymers

The aromatic polymers are of two general types. Those with benzene rings in the backbone and those with pendant benzene rings. Polycarbonates (Nos. 12-22) and polysulfone (no. 23) represent the first group. Polystyrene (No. 1-11, 53-55, 58, 74, 85) and styrene-acrylonitrile polymers (No. 94-100) are indicative of the second group. Polybutyleneterephthalate (No. 93) is another example of an aromatic polymer containing benzene rings in the backbone.

The aromatic polymers are characterized by ξ values larger than ≈ 3 . Those with $\dot{Q}_1'' > \dot{Q}_t''$ have LOI's greater than 0.21. The polycarbonate and polysulfone have lower "ideal" burning rates than do the polystyrenes. They also have lower H_c and larger L_g values, resulting in smaller values for B. The polystyrene containing flame retardant additive (No. 10-11, 54-55, 74, and 85) also have lower B numbers. The SAN polymers show inconsistent burning behaviors, as some contain large amounts of diene rubber, which greatly influence their combustion parameters. Generally, it can be said that aromatic polymers with benzene rings in their backbone tend to char more and burn less intensely than do those polymers with pendant benzene rings. The effect of Lewis acid salts on the burning behavior of polycarbonates (No. 12-22) are seen as an increases heat flux loss from the burning surface (\dot{Q}_1'').

c Wood

The combustion parameters of the wood fuels are also shown in Table I. The wood fuels burned with considerable charring. For most wood fuels, $\dot{Q}_1'' > \dot{Q}_t''$ and $LOI_{theo} > 0.21$. The "ideal" mass burning rates of the woods did not correlate to the density of the dried sample. The heat of combustion of the samples was taken as being constant and equal to that of cellulose. This approximation could lead to an error in the B number.

D Aliphatic Fuels

The aliphatic fuels, with the exception of "isooctane" tended to produce less smoke than did the aromatic fuels. The aliphatic hydrocarbons produced the most soot of the aliphatic fuels studied. The B number for the aliphatic liquied fuels tended to be larger than those of the aliphatic polymers. This is probably due to the considerably larger Lg associated with the polymers. The differences in Lg values offset the larger net heats of combustion of the liquied fuels. PVC and Saran formed considerable chars during combustion and would only burn in oxygen enriched atmosphere. The "theoretical" LOI values for these polymers, seen in Table I, are close to those determined experimentally.

V. Discussion

The combustion parameters listed in Table 1 suggest that the burning rates for the unmodified fuels are in this order:

Aromatic liquids > aliphatic liquids > wood \approx polystyrene > aliphatic polymers > polycarbonates and polysulfone.

Figure 2 shows the "ideal" mass burning rate plotted against the B number as calculated in equation (3a) for the fuels listed in Table 1. Regression analysis of the data into the form shown in equation (3) yields the following values.

$$\dot{M}_{\text{ideal}}'' = 12.09 \times 10^{-4} B^{0.82} \quad (8)$$

with a correlation coefficient (r) of 0.82. This suggests that equation (3) is a reasonable model for the burning behavior of the fuels investigated. The aromatic liquid fuels show the greatest departure from equation (8).

The "ideal" mass burning rates and B number for the aromatic polymers are shown in Figure 3. The polymer included in the figures are styrenics, polycarbonates, polysulfones, SAN and PBT. Linear regression analyses shows

$$\dot{M}_{\text{ideal}}'' = 13.68 \times 10^{-4} B^{0.72} \quad (9)$$

with $r = 0.90$. The high value for r attests to the goodness of the fit. The exponent n is close to the 0.75 suggested by Spalding¹³ for aromatic fuels.

Figure 4 shows the data for aromatic liquids. Regression analysis of the data yield the following numerical solution

to equation (3) for all aromatic fuels.

$$\dot{M}_{\text{ideal}}'' = 13.43 \times 10^{-4} B^{1.08} \quad (10)$$

with $r = 0.93$.

The addition of the aromatic liquids had little effect ($\sim 2\%$) upon the constant C of equation (3). The exponent n increased by 36% when the "ideal" mass burning rates of the aromatic liquids were considered, along with those of the aromatic polymers. The marked increases in the exponent can only be attributed to the large burning rate of the liquids. The rather high value for the correlation coefficient can also be attributed to the contribution of the aromatic liquids.

Table I gives the "ideal" mass burning rate and B number for the eight wood fuels. Regression analysis gives the following relationship for wood.

$$\dot{M}_{\text{ideal}}'' = 10.87 \times 10^{-4} B^{0.96} \quad (11)$$

The correlation coefficient of 0.86 is the lowest for any single fuel type studied. It is not much larger than the $r = 0.82$ for all 100 fuels. The B number may be in considerable error due to the assumption that all the woods have the same heat of combustion.

The "ideal" mass burning rates and B numbers for the aliphatic fuels are shown in Figure 5. Regression analysis of the data yield the following solution

$$\dot{M}_{\text{ideal}}'' = 7.00 \times 10^{-4} B^{0.95} \quad (12)$$

with a correlation coefficient of $r = 0.94$.

The exponent n suggests that for all materials except the aromatic polymers, the burning rate is dependent upon the oxygen content to the first power ($n = 0.95, 0.96$, and 1.08 , respectively for aliphatic, wood, and all aromatics). The low exponential value for the aromatic polymers could indicate degradation reactions.

Figure 6 is a linear plot of B versus L_g for all materials studied. The shape of the results indicates that a log-log plot would better fit the data. Figure 7 is such a plot. The relationship shown in equation (7) should also fit the data.

Regression analysis of the B and L_g value for all materials in Table I give the following numerical results for equation (7).

$$B = 747.49 \text{ Lg}^{-0.997} = \frac{747.49}{\text{Lg}} \quad (13)$$

with a correlation coefficient of $r = -0.99$. The analysis suggests that:

- (1) equation (3a) adequately defines B.
- (2) That $\frac{M_{O_2} \cdot H_c}{r}$ can be considered a constant.
- (3) B can be calculated from Lg values only without knowing the heat of combustion, or chemical formula of the fuel.
- (4) If $B \leq 1$, the fuel should not sustain combustion in the atmosphere ($M_{O_2} = 0.232$). That is, the "apparent" heat of O_2 gasification is greater than the net heat of combustion per gm of fuel.

Other curve fits, such as log or exponentials, were not carried out on the data. This is not to say that some other fit might not be as good as the power curve of equation (13).

VI. Summary

Mass burning rate studies have been carried out on 138 fuels. The "ideal" mass burning rates of 100 fuels ~~have been~~ correlated to the mass transfer number B. The correlation suggests that the fuels can be grouped into structural classes, aromatic, aliphatic, solid, liquid, etc., for burning behavior. The B number ~~has been~~ related to the "apparent" heat of gasification by the equation

$$B = \frac{747.49}{r}$$

The steady-state burning behavior of the fuels studied ~~can be~~ ranked as follows (in order of decreasing intensity):

Aromatic liquids > aliphatic liquids > wood > polystyrenes > aliphatic polymers > polycarbonates and polysulfones.]

But, modified

> = greater than

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| FUEL | ρ (cal/cm ³ sec) | ρ_c (cal/cm ³ sec) | ρ_c (cal/cm ³ sec) | L_0 (cal/gm) | M^* (deal) (gm/cm ³ sec) | H_c (d) (cal/gm) | β | LOF _{theo} | A |
|--|-------------------------------------|---------------------------------------|---------------------------------------|-------------------|--|-----------------------|---------|---------------------|-----|
| 1 STYRON 466U | 3.83 | .8 | .65 | 402 | 2.00000E-03 | 9925 | 1.87 | .17 | 752 |
| 2 STYRON 430U | 4.05 | .85 | .58 | 312 | 2.74000E-03 | 9925 | 2.41 | .143 | 752 |
| 3 STYRON 412D | 3.99 | .84 | .64 | 450 | 1.86000E-03 | 9925 | 1.67 | .16 | 752 |
| 4 STYRON 470 | 4.47 | .94 | .67 | 299 | 3.14000E-03 | 9925 | 2.51 | .13 | 750 |
| 5 STYRON 492U | 3.21 | .68 | .57 | 310 | 2.18000E-03 | 9925 | 2.42 | .178 | 750 |
| 6 STYRON 475U | 3.95 | .83 | .68 | 295 | 2.81000E-03 | 9925 | 2.35 | .172 | 752 |
| 7 STYRON 475 | 3.01 | .63 | .46 | 474 | 1.33000E-03 | 9925 | 1.59 | .153 | 754 |
| 8 XP-70502 | 3.22 | .68 | .48 | 242 | 2.79000E-03 | 9925 | 2.53 | .149 | 612 |
| 9 XP-6073 | 3.6 | .76 | .49 | 337 | 2.24000E-03 | 9925 | 2.33 | .136 | 752 |
| 10 STYRON 6021 | 5.34 | 1.12 | 1.47 | 528 | 2.12000E-03 | 9925 | 1.42 | .275 | 750 |
| 11 XP-7000 | 5.02 | 1.05 | 1.24 | 552 | 1.91000E-03 | 9925 | 1.36 | .247 | 751 |
| 12 LEXAN 101-111 | 5.35 | 1.12 | 1.44 | 909 | 1.24000E-03 | 7400 | .83 | .269 | 754 |
| 13 LEXAN 101+.01SULFADIAZINE | 5.9 | 1.24 | 2.2 | 767 | 1.28000E-03 | 7400 | .79 | .373 | 754 |
| 14 LEXAN 101+.10XSULFADIAZINE | 6.97 | 1.46 | 2.88 | 1086 | 1.35000E-03 | 7400 | .7 | .413 | 740 |
| 15 LEXAN 101+.10XSULFADIAZINE | 5.6 | 1.18 | 1.54 | 908 | 1.30000E-03 | 7400 | .83 | .279 | 754 |
| 16 LEXAN 101+.01ZFRS (a) | 5.15 | 1.08 | 1.86 | 872 | 1.24000E-03 | 7400 | .87 | .361 | 759 |
| 17 LEXAN 101+.10ZFRS | 5.59 | 1.18 | 2.11 | 802 | 1.47000E-03 | 7400 | .94 | .377 | 754 |
| 18 LEXAN 101+.50ZFRS | 6.34 | 1.33 | 2.55 | 773 | 1.72000E-03 | 7400 | .98 | .402 | 758 |
| 19 MERLON M-40 | 5.31 | 1.12 | 1.5 | 1041 | 1.05000E-03 | 7400 | .71 | .282 | 753 |
| 20 MERLON M-40+.01ZKBS (b) | 6.37 | 1.34 | 2.25 | 1087 | 1.23000E-03 | 7400 | .7 | .353 | 761 |
| 21 MERLON M-40+.10ZKBS | 4.3 | .9 | 1.53 | 1062 | 9.50000E-04 | 7400 | .71 | .356 | 754 |
| 22 MERLON M-40+.10ZKBS | 4.3 | .9 | 1.34 | 883 | 1.02000E-03 | 7400 | .86 | .312 | 759 |
| 23 UDEL P1700 | 4.1 | .86 | 1 | 1124 | 6.80000E-04 | 7528 | .68 | .244 | 764 |
| 24 PONDERROSA PINE | 3.76 | .79 | .77 | 667 | 1.18000E-03 | 4181 | 1.23 | .205 | 820 |
| 25 RED OAK | 3.89 | .82 | .94 | 617 | 1.96000E-03 | 4181 | 1.97 | .242 | 821 |
| 26 BLACK CHERRY | 5.04 | 1.06 | 1.09 | 719 | 1.47000E-03 | 4181 | 1.14 | .216 | 820 |
| 27 WHITE OAK | 4.06 | .85 | 1.07 | 338 | 2.57000E-03 | 4181 | 2.43 | .264 | 821 |
| 28 HARD MAPLE | 4.08 | .86 | 1.04 | 483 | 1.77000E-03 | 4181 | 1.7 | .255 | 821 |
| 29 MICHIGAN CEDAR | 4.39 | .92 | 1.1 | 539 | 1.71000E-03 | 4181 | 1.53 | .251 | 825 |
| 30 WALNUT | 3.25 | .68 | .59 | 772 | 8.80000E-04 | 4181 | 1.06 | .182 | 818 |
| 31 AFRICAN MANHOBANY | 5.42 | 1.14 | 1.24 | 667 | 1.71000E-03 | 4181 | 1.23 | .229 | 820 |
| 32 METHANOL | 2.14 | .45 | .17 | 287 | 1.57000E-03 | 5341 | 2.88 | .081 | 827 |
| 33 ETHANOL | 2.07 | .44 | .25 | 239 | 1.82000E-03 | 7122 | 3.31 | .121 | 791 |
| 34 N-PROPANOL | 2.49 | .52 | .42 | 207 | 2.52000E-03 | 7995 | 3.73 | .17 | 773 |
| 35 N-BUTANOL | 2.45 | .52 | .41 | 191 | 2.70000E-03 | 8869 | 4.16 | .167 | 795 |
| 36 N-HEXANOL | 1.87 | .39 | .27 | 197 | 2.00000E-03 | 9306 | 3.89 | .144 | 766 |
| 37 I-PROPANOL | 2.22 | .47 | .24 | 193 | 2.41000E-03 | 7900 | 3.94 | .109 | 764 |
| 38 N-HEPTANE | 2.06 | .38 | .25 | 112 | 3.84000E-03 | 11480 | 6.27 | .119 | 759 |
| 39 N-OCTANE | 2.75 | .53 | .44 | 130 | 4.45000E-03 | 11405 | 5.82 | .158 | 757 |
| 40 ISO-OCTANE | 3.36 | .7 | .56 | 106 | 6.65000E-03 | 11418 | 7.15 | .167 | 758 |
| 41 PNMA | 1.95 | .41 | .22 | 339 | 1.21000E-03 | 6377 | 2.17 | .113 | 734 |
| 42 HDPE | 2.53 | .53 | .38 | 517 | 1.03000E-03 | 11148 | 1.38 | .15 | 713 |
| 43 PP | 3.42 | .72 | .61 | 545 | 1.32000E-03 | 11137 | 1.29 | .178 | 703 |
| 44 UHMWPE | 2.15 | .45 | .33 | 517 | 8.70000E-04 | 11148 | 1.36 | .153 | 703 |
| 45 BENZENE | 7.33 | 1.54 | .93 | 119 | .01295 | 10015 | 5.95 | .126 | 757 |
| 46 TOLUENE | 10.04 | 2.11 | 1.24 | 125 | .01688 | 10143 | 5.95 | .133 | 744 |
| 47 STYRENE | 8.77 | 1.84 | 1.45 | 141 | .01307 | 10048 | 5.26 | .165 | 739 |
| 48 ANISOLE | 3.72 | .78 | .46 | 141 | 5.52000E-03 | 8381 | 5.46 | .125 | 770 |
| 49 BENZYL ALCOHOL | 7.32 | 1.54 | 1.22 | 202 | 7.61000E-03 | 8281 | 3.77 | .167 | 762 |
| 50 P-XYLENE | 6.93 | 1.46 | 1.05 | 127 | .01146 | 10259 | 5.91 | .151 | 751 |
| 51 O-XYLENE | 7.83 | 1.64 | 1.23 | 132 | .01245 | 10289 | 5.7 | .157 | 752 |
| 52 BENZONITRILE | 4.07 | .86 | .48 | 180 | 4.75000E-03 | 8393 | 4.23 | .117 | 741 |
| 53 STYRON 685 | 4.26 | .9 | .74 | 619 | 2.14000E-03 | 9925 | 1.79 | .175 | 746 |
| 54 STYRON 685+10ZFR-3008A (c) | 3.86 | .81 | .74 | 521 | 1.55000E-03 | 9925 | 1.43 | .193 | 745 |
| 55 STYRON 685+10ZFR-3008A+5ZS ₂ | 3.95 | .83 | .79 | 556 | 1.49000E-03 | 9925 | 1.34 | .201 | 745 |
| 56 N-HEXANE | 3.19 | .67 | .42 | 104 | 6.44000E-03 | 11570 | 7.31 | .136 | 760 |
| 57 CYCLOHEXANE | 2.48 | .56 | .32 | 109 | 5.16000E-03 | 11172 | 6.97 | .119 | 759 |
| 58 XP-71001 | 4.53 | .96 | .78 | 394 | 2.41000E-03 | 9925 | 1.99 | .172 | 744 |
| 59 ACETONE | 1.7 | .36 | .17 | 136 | 2.62000E-03 | 7368 | 5.71 | .103 | 777 |
| 60 N-HEPTANOL | 2.35 | .49 | .37 | 203 | 2.43000E-03 | 9509 | 3.76 | .156 | 762 |
| 61 N-OCTANOL | 2.58 | .54 | .43 | 209 | 3.60000E-03 | 9493 | 1.65 | .165 | 763 |
| 62 T-BUTANOL | 2.11 | .44 | .3 | 147 | 3.01000E-03 | 8490 | 5.17 | .144 | 760 |
| 63 N-BUTYLAMINE | 1.34 | .33 | .19 | 129 | 2.55000E-03 | 9716 | 5.92 | .123 | 764 |
| 64 ETHYLENE DICHLORIDE | 1.75 | .37 | .28 | 95 | 3.87000E-03 | 2738 | 6.89 | .158 | 655 |
| 65 NITROBENZENE | 5.1 | 1.07 | .74 | 147 | 7.28000E-03 | 6004 | 5.81 | .145 | 854 |
| 66 ANILINE | 3.04 | .64 | .35 | 194 | 3.29000E-03 | 9719 | 3.92 | .116 | 760 |
| 67 BENZYL CHLORIDE | 6.32 | 1.33 | 1.14 | 120 | .01105 | 7002 | 6.13 | .181 | 73A |
| 68 HIBK | 2.47 | .52 | .33 | 129 | 4.03000E-03 | 9902 | 5.71 | .133 | 762 |
| 69 MEK | 2.1 | .44 | .26 | 136 | 3.24000E-03 | 8091 | 5.46 | .126 | 770 |
| 70 ETHYL FORMATE | 2.5 | .52 | .39 | 112 | 4.69000E-03 | 5286 | 7.25 | .156 | 817 |
| 71 ETHYL ACETATE | 2.08 | .44 | .29 | 113 | 3.84000E-03 | 4093 | 6.88 | .141 | 777 |
| 72 PROPIONIC ACID | 2.01 | .42 | .3 | 164 | 2.56000E-03 | 4926 | 4.62 | .15 | 758 |
| 73 N,N-DIMETHYLANILINE | 3.31 | .7 | .5 | 151 | 4.61000E-03 | 9428 | 5.1 | .15 | 770 |
| 74 XP-70512 | 5.93 | 1.25 | 2.08 | 650 | 1.72000E-03 | 9925 | 1.15 | .351 | 748 |
| 75 N-PENTANE | 2.89 | .61 | .38 | 93 | 6.52000E-03 | 11531 | 6.12 | .131 | 755 |
| 76 N-DECANE | 2.86 | .6 | .45 | 156 | 3.84000E-03 | 11316 | 4.82 | .156 | 752 |
| 77 DIETHYLAMINE | 1.23 | .26 | .13 | 106 | 2.44000E-03 | 9821 | 7.26 | .106 | 770 |
| 78 TRIETHYLAMINE | 1.71 | .36 | .2 | 110 | 3.26000E-03 | 10246 | 7.02 | .117 | 772 |
| 79 DI-BUTYLAMINE | 1.55 | .33 | .2 | 164 | 1.99000E-03 | 10450 | 4.68 | .127 | 768 |
| 80 PYRIDINE | 4.26 | .89 | .57 | 146 | 6.12000E-03 | 8407 | 3.28 | .135 | 824 |
| 81 ACETONITRILE | 2.38 | .5 | .28 | 208 | 2.40000E-03 | 7367 | 1.84 | .119 | 798 |
| 82 BROMOBENZENE | 2.59 | .54 | .85 | 89 | 6.12000E-03 | 4643 | 8.46 | .129 | 753 |
| 83 SARAN X0-5230.14 | 7.72 | 1.62 | 5.83 | 749 | 1.71000E-03 | 2460 | .82 | .755 | 782 |
| 84 PVC | 6.64 | 1.39 | 2.68 | 567 | 2.12000E-03 | 4298 | 1.18 | .403 | 777 |
| 85 STYRON 6087 | 4.63 | .97 | 1.33 | 513 | 1.90000E-03 | 9925 | 1.46 | .296 | 748 |
| 86 BUTYL ACETATE | 1.73 | .36 | .25 | 122 | 2.98000E-03 | 7329 | 6.31 | .143 | 749 |
| 87 N-DECANOL | 2.83 | .59 | .44 | 210 | 2.83000E-03 | 9946 | 3.43 | .154 | 763 |
| 88 T-PENTANOL | 2.34 | .49 | .33 | 165 | 2.98000E-03 | 3956 | 1.63 | .14 | 744 |
| 89 ALLYL ALCOHOL | 2.49 | .52 | .21 | 210 | 2.49000E-03 | 7617 | 1.82 | .085 | 803 |
| 90 ETHYLENE GLYCOL | 3.11 | .65 | .35 | 326 | 2.00000E-03 | 4542 | 3.51 | .114 | 817 |
| 91 PROPYLENE GLYCOL | 2.23 | .47 | .22 | 394 | 1.59000E-03 | 5671 | 2.66 | .094 | 787 |
| 92 BENZOYL CHLORIDE | 3.4 | .71 | .54 | 132 | 5.41000E-03 | 5569 | 5.72 | .158 | 756 |
| 93 PBT | 5.57 | 1.17 | 1.08 | 491 | 2.38000E-03 | 6276 | 1.57 | .194 | 770 |
| 94 TYRIL 880-27 | 1.9 | .4 | .14 | 371 | 1.08000E-03 | 9534 | 2.03 | .074 | 755 |
| 95 TYRIL 747 | 4.71 | .99 | .77 | 339 | 2.97000E-03 | 9610 | 2.22 | .163 | 753 |
| 96 BRD/RC 3231/3229 | 11.38 | 2.39 | 2.08 | 772 | 3.10000E-03 | 9129 | .99 | .183 | 745 |
| 97 BRD/RC 3183/3206 | 10.54 | 2.22 | 1.97 | 749 | 2.94000E-03 | 9054 | 1.02 | .187 | 744 |
| 98 CYCOPAK 920 | 4.43 | .93 | .82 | 371 | 2.37000E-03 | 9902 | 1.95 | .185 | 745 |
| 99 SARX 210 | 2.34 | .49 | .42 | 467 | 1.05000E-03 | 7168 | 1.68 | .179 | 784 |
| 100 EX 2023 | 6.49 | 1.34 | 1.09 | 528 | 2.57000E-03 | 7175 | 1.44 | .168 | 760 |

(a) $PM = \left(\text{HC} - \text{C} - \text{SO}_2 - \text{C} \right)_n$

(b) CBS = POTASSIUM BENZENE SULFONATE

(c) PM-3008A = Decabromodiphenyl oxide

(d) Literature values

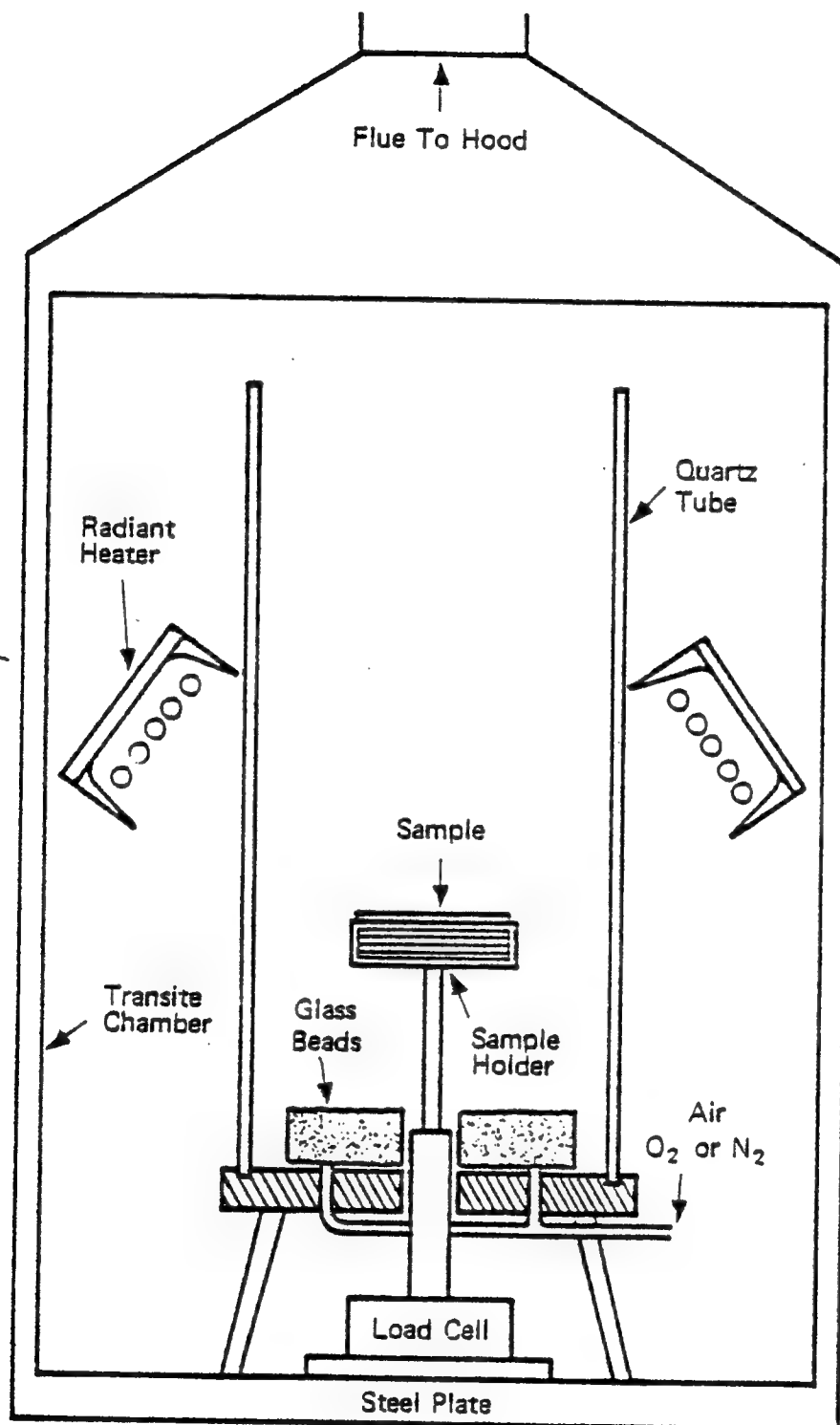


FIGURE 1 - The Mass Burning
Rate Apparatus

BURNING RATE VS. "B"

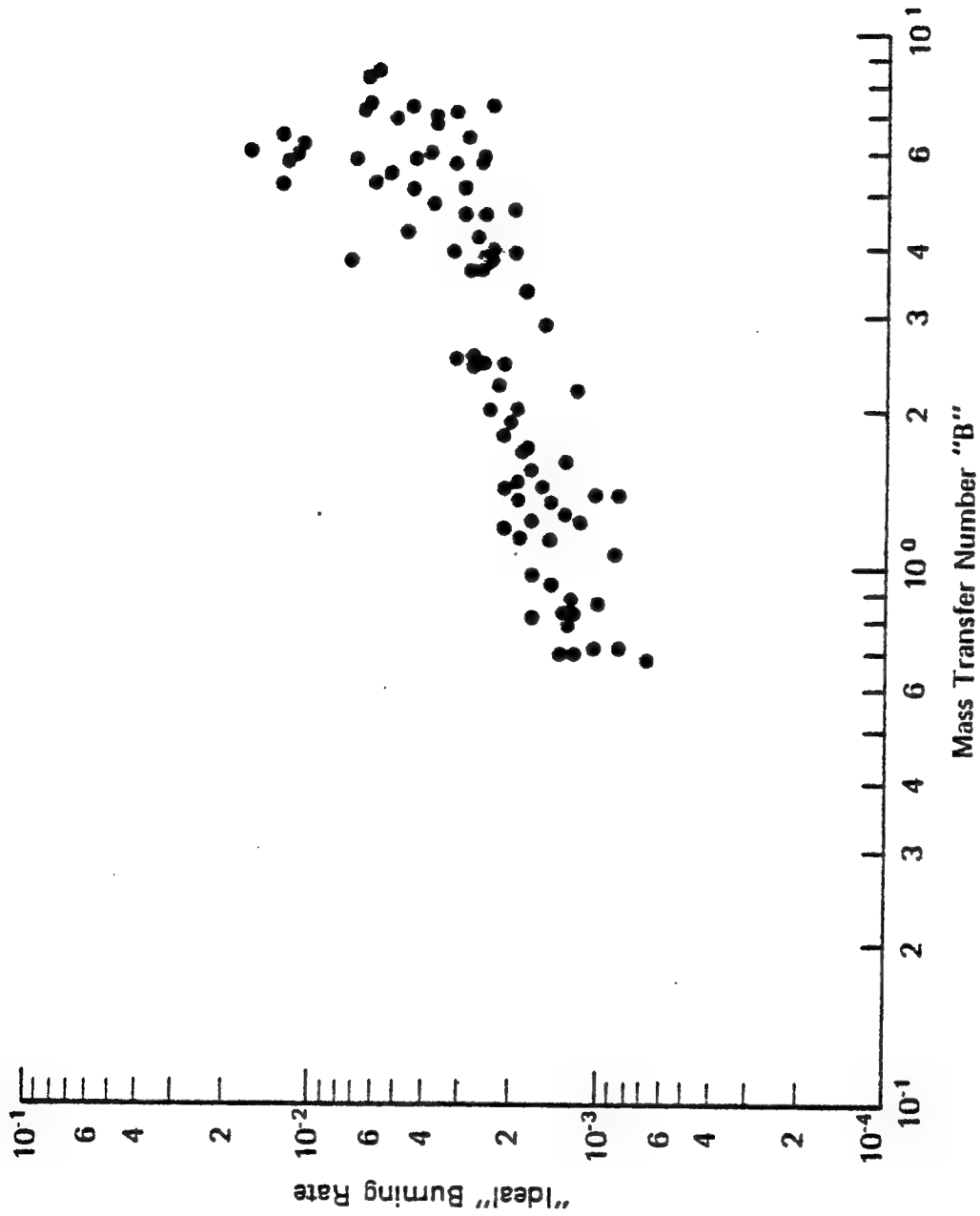


FIGURE 2 - "Ideal" Burning
Rate and Mass Transfer
Number for all fuels

MBR OF AROMATIC POLYMERS

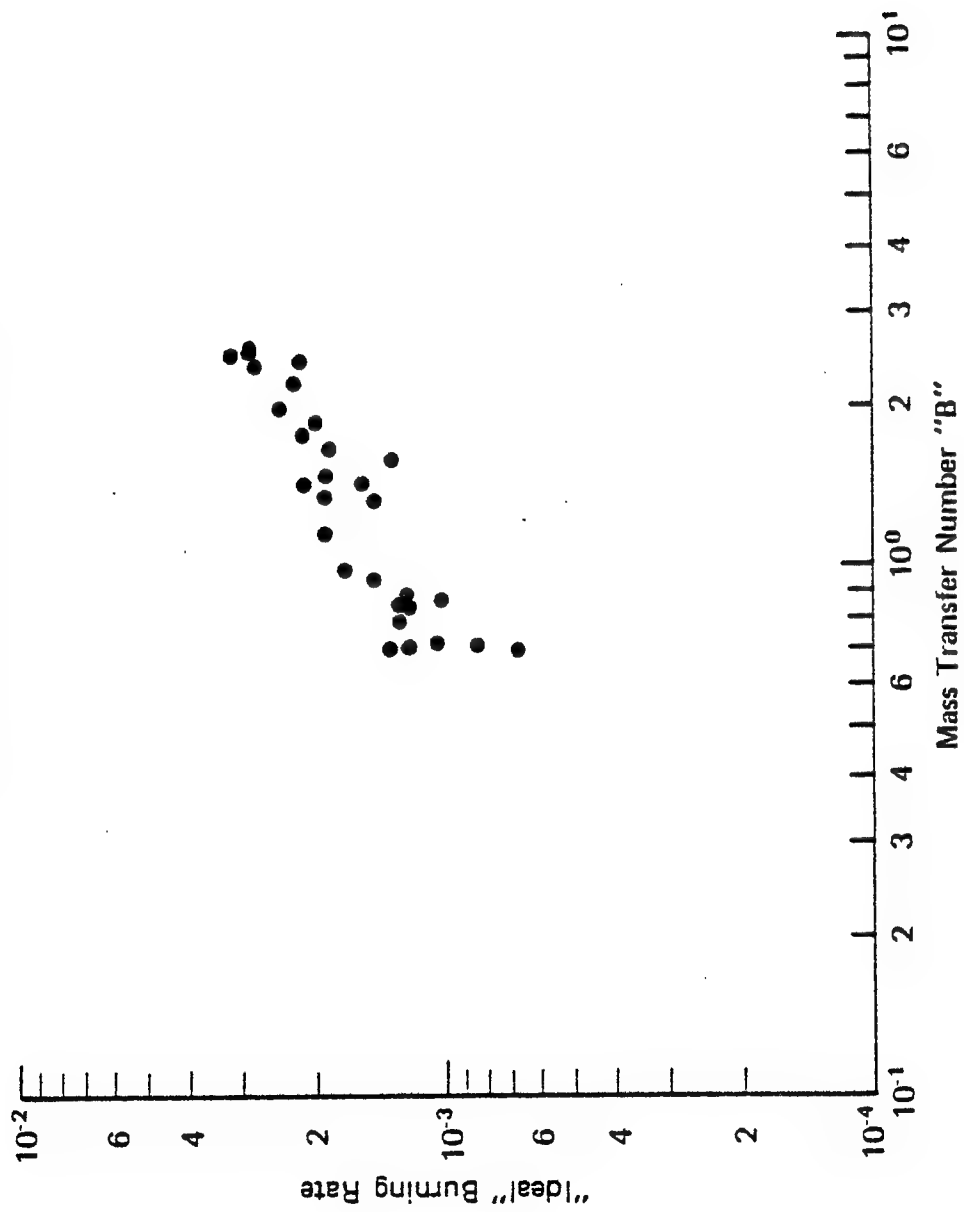


FIGURE 3 - "Ideal" Burning Rate and Mass Transfer number for aromatic polymers

MBR OF AROMATIC LIQUIDS

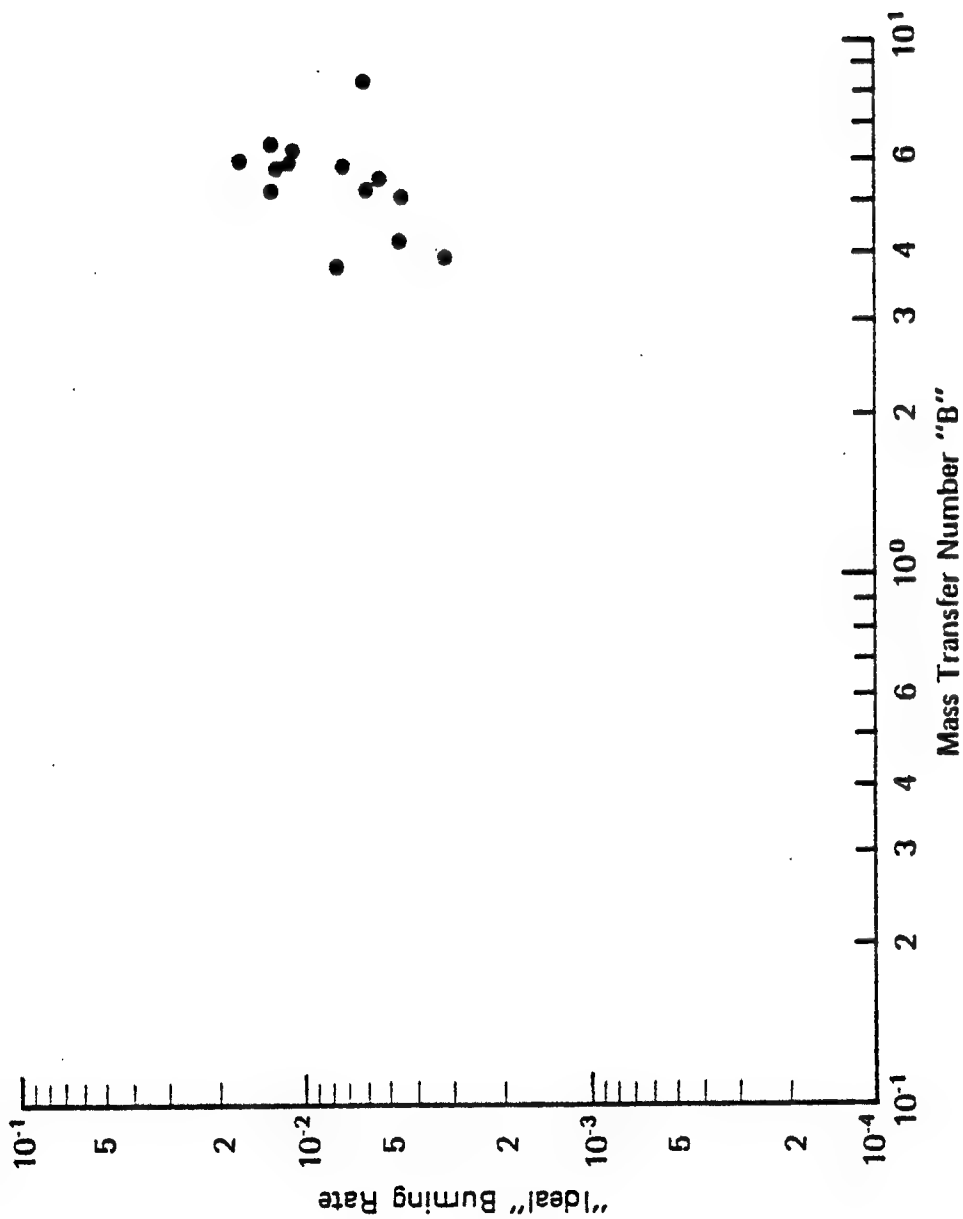


FIGURE 4 - "Ideal" Burning Rate and
Mass Transfer Number
for Aromatic Liquids

MBR OF ALIPHATIC FUELS

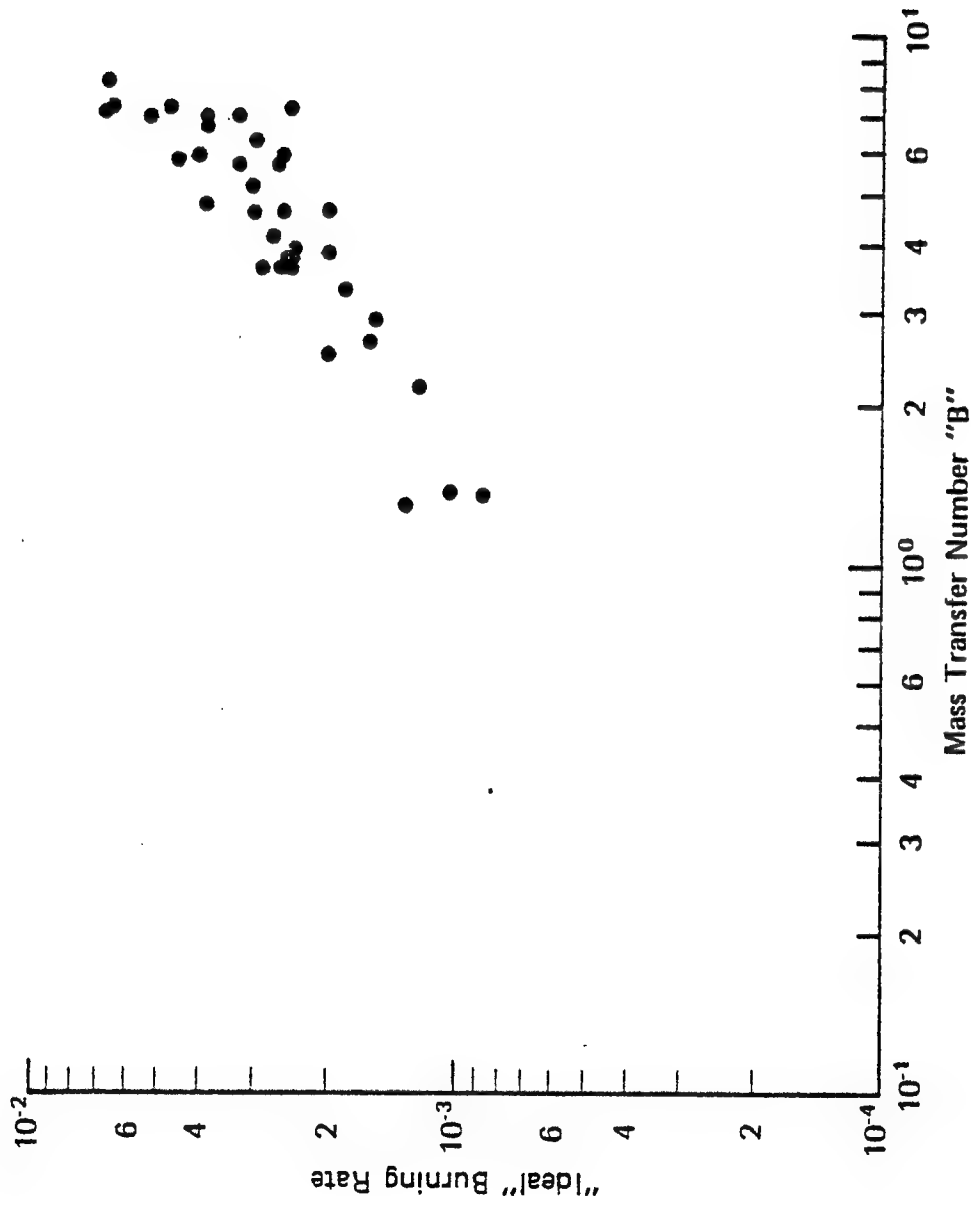


FIGURE 5 - "Ideal" Burning Rate and
Mass Transfer Number of Aliphatic
Fuels

"APPARENT" HEAT OF GASIFICATION VS. "B"

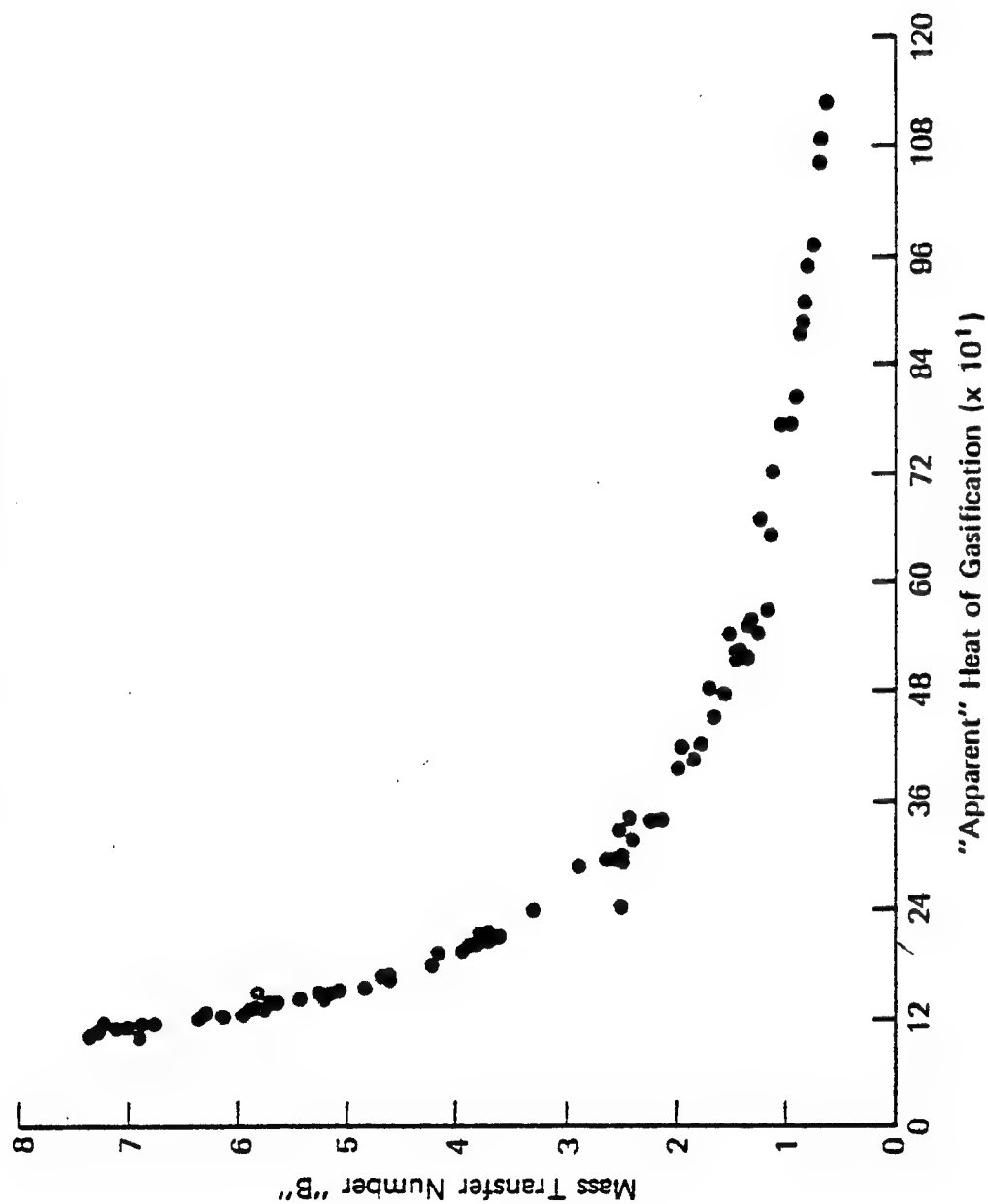


FIGURE 6 - Linear plot of B vs.
Lg for all fuels

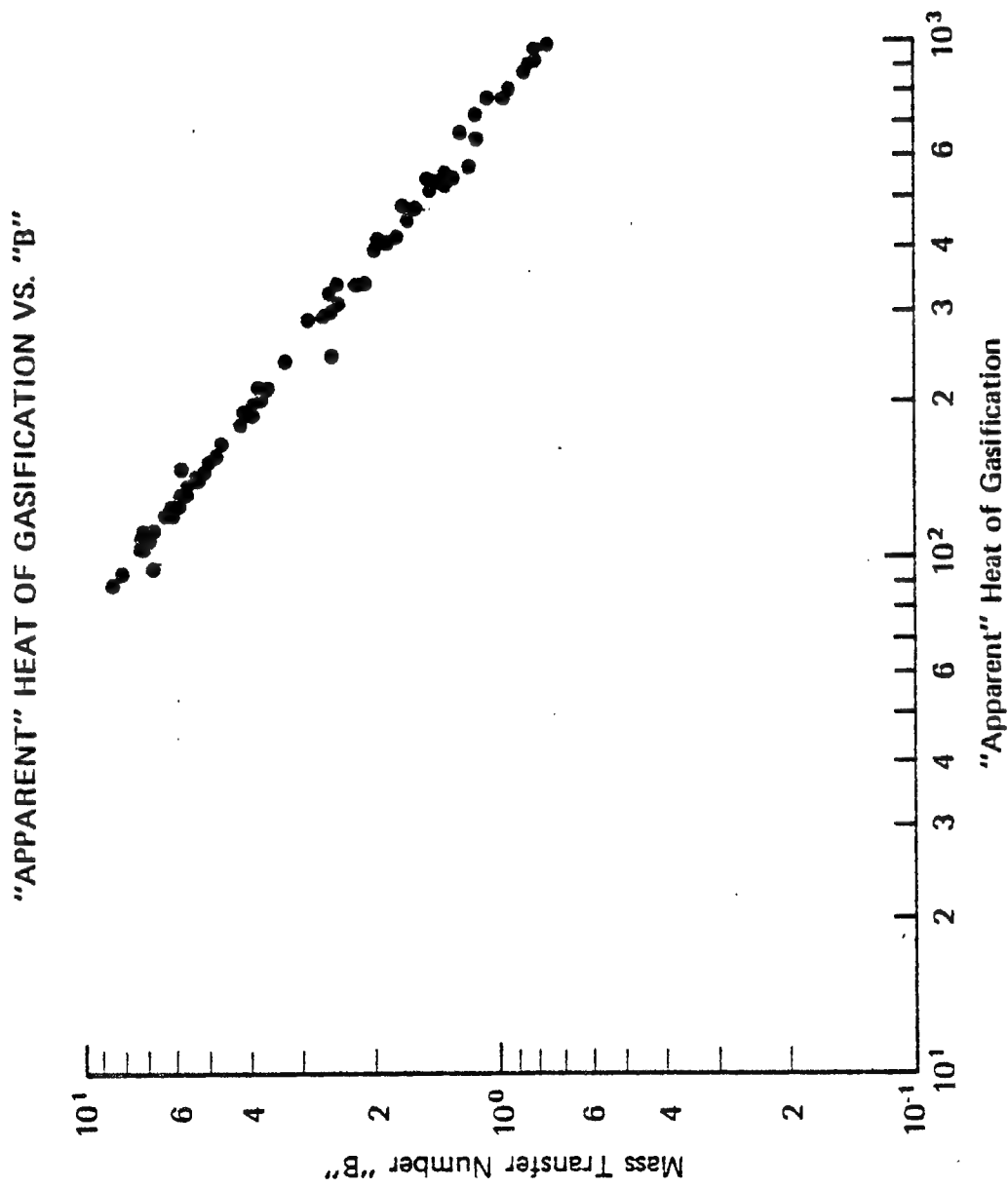


FIGURE 7 - Log - Log Plot of
B vs. Lg for all fuels

FIRE PERFORMANCE STUDIES ON POLYETHERIMIDE

D.E. FLORYAN AND G.L. NELSON

GENERAL ELECTRIC COMPANY
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A new Engineering Plastic called polyetherimide has been developed by the General Electric Co. This material is an amorphous thermoplastic characterized by high heat distortion temperature (200°C at 264 psi), high mechanical strength (tensile strength 15000 psi, flexural strength 21,000 psi), high flexural modulus (480,000 psi) and good electrical properties which are stable across a wide range of temperature and frequency. The flame retardancy characteristics are excellent without the addition of flame retardant additives. Measurements of a variety of laboratory scale flammability properties indicate that the material is difficult to ignite, with Setchkin Self Ignition temperature of 535°C and V-O UL94 rating. Flame spread index in the Radiant Panel test is low ($I = 2.7$) and the oxygen index is high (47%). NBS smoke chamber results show a low specific optical density throughout the 20 minute test. ($D_{4 \text{ min}} = 0.7$, $D_m = 31$, flaming mode), and combustion product toxicity studies show comparable results to polycarbonate, with carbon monoxide apparently the principal toxicant.

INTRODUCTION

Engineering Plastics, as their name implies, are a family of synthetic polymers which provide an improved property balance for a variety of stringent applications. These materials are generally characterized by higher mechanical properties, higher temperature capability, and better flame retardancy than commodity plastics, and offer improvements in processing flexibility, freedom of design and overall assembly economics over metal, ceramics and glass. Typical thermoplastics in this family of materials which have seen increasing use over the last decade are polycarbonate, modified polyphenylene oxide, the polysulfones, and certain flame retardant and filled versions of nylon and polyester.

The General Electric Company has recently developed a new member of the Engineering Plastics Family which has been given the name polyetherimide. This material, or family of materials, is based on new chemistry which has resulted in a thermoplastic resin with unique mechanical, thermal and flame retardancy characteristics, combined with processing characteristics which make it attractive for a variety of engineering uses.

This paper will discuss the properties of polyetherimide, with particular emphasis on the results of flammability testing which has been conducted to date.

POLYETHERIMIDES

Polyetherimides are materials which contain regular repeating ether and imide linkages, as the name suggests. A general chemical structure of these resins is shown in Figure 1.

The repeating aromatic imide units in this molecule are connected by aromatic ether units to give a polymer with flexible linkages for good melt flow characteristics, while retaining sufficient stiffness for good engineering properties. In addition, designing the polymer backbone with highly aromatic character combined with ether and imide connecting units lends itself to good thermal stability, and flame retardancy.

PHYSICAL PROPERTIES

Typical mechanical properties of this polyetherimide are shown in Table 1. This polymer has proven to be exceptionally strong, with a tensile strength at yield of 15,000 psi and flexural strength of 21,000 psi. The flexural modulus of the material, at 480,000 psi, is outstanding for an unfilled thermoplastic resin. And the material has practical toughness, with a Gardner impact strength of over 320 inch-pounds.

In terms of thermal properties (Table 2), the polymer has a glass transition temperature of 217°C and heat distortion temperature at 264 psi of 200°C. The small difference between the softening point and the heat distortion temperature indicates that the polymer has very good properties retention at elevated temperatures. This is confirmed by measurements of the flexural modulus of the material vs. temperature, which show that even at 180°C, the flexural modulus is over 300,000 psi.

Polyetherimide also has very good electrical properties, as shown in Table 3. Its dielectric constant and dissipation factor are comparable to other high performance engineering materials at room temperature, but in addition these values show little change at elevated temperature across a wide range of frequency. This is a unique property, and very useful when combined with the high temperature capability of the polymer. Its dielectric strength is high as well, and it displays good surface and volume resistivity.

The processability of the material is quite good, as expected (Figure 2). The melt viscosity of the resin vs. shear rate is comparable to polycarbonate or polysulfone rather than typical polyimides, albeit at a higher temperature. This allows the material to be easily injection molded or extruded into a variety of useful shapes.

LABORATORY SCALE FLAMMABILITY TESTING

Polyetherimide has been evaluated in a variety of laboratory tests designed to establish a fire performance profile. Combustibility of a synthetic material can depend as much on fire conditions as on the polymer composition, and these tests indicate the behavior of the material in several key aspects of material fire performance:

- (1) Ease of ignition - how readily a material ignites.
- (2) Flame spread - how rapidly fire spreads across a polymer surface.
- (3) Fire endurance - how rapidly fire penetrates a wall or barrier.
- (4) Rate of heat release - how much heat is released how quickly.
- (5) Ease of extinction - how rapidly the flame chemistry leads to extinction.
- (6) Smoke evolution.
- (7) Toxic gas generation.

Used together, these tests can provide useful material information. In Table 4 are presented data for polyetherimide (0.060 inch) and comparable values for three grades of polycarbonate, the highest performance commonly used engineering plastic, and polyethersulfone in several standard test conditions.

IGNITABILITY

Two kinds of tests are used to measure ignitability. In the first, the temperatures necessary to cause sufficient decomposition to generate volatile fuel which will either spontaneously ignite or which can be ignited by a pilot flame are measured. The apparatus used is the Setchkin Apparatus (ASTM D 1929). Ignition temperatures are dependent upon the rates and intensity of heat application thus the temperatures obtained are of use only in a relative sense. Of particular interest is the fact that most plastics have self-ignition and flash-ignition temperatures considerably above that of wood. For example, polyethylene has a self-ignition temperature of 349°C, compared with 260°C for white pine. Ignition of polyetherimide clearly occurs, but at elevated temperatures, with a Setchkin Self-Ignition Temperature of 535°C.

The second kind of ignitability test involves the application of prescribed bunsen burner flames to small polymer samples for short fixed periods of time and determining whether sustained ignition occurs after the removal of the bunsen flame. Though the term is no longer used because it could be misleading, it was in such kinds of tests that the term "self-extinguishing" originated. Both horizontal or vertical samples can be used. UL-94 is a common test method used of this type. Polyetherimide is V-0 at 0.060 inches in this test.

Recognized as one of the more severe, however, is the 60 second flame application of the FAR 25.853a vertical bunsen burner test. Polyetherimide has relatively short extinguishing times in this test (2.1 sec).

FLAME SPREAD

The largest laboratory scale flame spread test commonly applied to engineering plastics in the United States is the ASTM E162 Radiant Panel Test. The test apparatus is shown schematically in Figure 3. A 6 by 18 inch sample is inclined at 30° to a 12 by 18 inch radiant panel at 670°C. A small pilot flame is at the top of the sample to ignite the volatile off gases. One measures the rate of sample burning down the sample (F_s) and the heat rise associated with that burning in the flue stack above the burning sample (Q). These combined values determine the index (I_s) for a material ($I_s = F_s \times Q$). Exterior grade plywood shows an I_s of 169. Polyetherimide has relatively low radiant panel values, with an I_s of only 2.7.

EASE OF EXTINCTION

A test frequently cited is the oxygen index test (ASTM D2863). Most engineering plastics brochures report oxygen indices. In the oxygen index test a 6.5mm wide, 3mm thick, 70 to 150mm long sample is placed in the center of a glass cylinder (Figure 4). At the base of the cylinder air is fed in which the percentage of oxygen can be varied. A small gas flame is applied to the top of the sample until the sample is well lit. If sustained combustion occurs the test is repeated at a lower oxygen concentration in the test air until an atmosphere is reached which will not sustain continued combustion of the sample. The oxygen index of a specimen is the minimum percentage of oxygen in an oxygen/nitrogen atmosphere which will just sustain combustion of the specimen. Extensive use of oxygen index has been made for research purposes. While several authors have called oxygen index an ignition test, since the ignition flame is unspecified, and the application time of that flame is also unspecified, oxygen index is not an ignition test but clearly a measure of ease of extinction. For comparison red oak has a value of 24.6 and plywood of 22.4. Clearly at 47 polyetherimide has an exceptional oxygen index for an unflame-retarded resin.

To put these values in perspective, in Figure 5 is given a pictorial general comparison of UL-94 data with that from oxygen index for a variety of thermoplastic materials. Non-flame retardant (HB rated) materials have oxygen indices centered at 20, V-2 materials at 26, V-1 materials at 28, and V-0 materials at 29. As expected in the case of V-0 materials a trend to higher oxygen indices is also seen. A clear line can be drawn at 25, separating HB materials from the materials exhibiting flame retardant characteristics in UL-94. Since UL-94 measures ignitability and oxygen index measures ease of extinction, only a qualitative relationship would be expected as is observed. Polyetherimide is a V-0 material at 0.060 thickness. Again, its exceptional oxygen index value is demonstrated.

SMOKE

Smoke, defined as light-obscuring airborne materials, largely carbon particles and liquid droplets, has been studied thoroughly and a number of techniques for evaluating smoke behavior have been developed.

Smoke can be trapped and weighed, or measured indirectly using light transmittance techniques. The NBS smoke chamber (ASTM E662) and the XP-2 (ASTM D2843) smoke chamber use the latter approach. In the XP-2 smoke chamber, (Figure 6) one square inch (by 1/4 inch) of material is exposed to a pilot flame in a closed chamber with several small ventilation ports. A light source and photocell measures light transmission in a horizontal plane above the sample.

The XP-2 smoke value for polyetherimide is relatively low at 28.

The National Bureau of Standards method measures the light obscuration due to smoke generated by materials under both flaming and non-flaming (radiant heat) conditions (Figure 7). In this test a 3 x 3 inch sample is rigidly mounted in an 18 ft³ closed chamber. An electric furnace provides radiant heat (2.5 watts/cm²) for non-flaming conditions. Pilot flames are applied to the face of the sample for flaming conditions. Like all high temperature plastics, polyetherimide shows little smoke under smoldering conditions (Dmax = 0.4). Values under flaming conditions are also comparatively low (Dmax = 31).

TOXIC GASES

All organic materials produce toxic products on burning -- if only carbon monoxide and carbon dioxide, which can be toxic in sufficient quantities. However, engineering resins are likely to be no more toxic than wood. Studies of polystyrene, polycarbonate, and polyphenylene oxide based resins suggest this, with carbon monoxide having been shown as the primary toxicant (1).

A sample of polyetherimide was evaluated for toxicity of combustion gases, using the USF-NASA toxicity screening test method. In this test, a sample of the polyetherimide is pyrolyzed in a horizontal tube furnace and the gases generated are conveyed to an exposure chamber containing test mice (Fig. 8). The responses of the mice are monitored for a period of at least 30 minutes, and gas samples from the chamber are analyzed. This method is intended to indicate which materials may be more toxic under specified test conditions, and not necessarily to explain why they are more toxic. Readers are referred to earlier papers for test details (2-7). In the present work sixteen different sets of test conditions of the USF-NASA toxicity screening test method were used in the evaluation of polyetherimide. These consisted of eight temperature programs, without forced air flow and with normal 1 L/min air flow.

1. 200 to 800°C rising temperature, 40°C/min
2. 800°C fixed temperature
3. 700°C fixed temperature
4. 600°C fixed temperature
5. 500°C fixed temperature
6. 400°C fixed temperature
7. 300°C fixed temperature
8. 200°C fixed temperature

The rising temperature program at 40°C/min from 200 to 800°C is intended to simulate the pre-flashover conditions of a developing fire, and to average the response to the different temperatures encountered over this range. This particular temperature program without forced air flow has been used to evaluate a considerable number of materials (2-4). Under these test conditions, designated as Procedure B, the polyetherimide sample exhibited a time to death of 17.4±0.3 min. Comparison with other generic polymers indicates that this material compares favorably with the majority of generic polymers under these test conditions. In Table 5 a comparison of results for polyetherimide is made with four representative materials under a variety of test conditions (longer times to death are a more favorable result).

The times to various animal responses are presented in Table 6 for the tests without forced air flow, and in Table 7 for the tests with nominal 1 L/min air flow. No toxic responses were observed under these particular test conditions at 400°C and lower temperatures, both without forced air flow and with nominal 1 L/min air flow. Production of toxic gases at these temperatures did not appear to be significant. The less than 100 percent mortality occurring at 500°C fixed temperature indicates that the threshold temperature for lethal effects under these particular test conditions may be about or slightly below 500°C. Times to the various animal responses progressively decreased with increasing temperature. This effect may be due to more rapid decomposition, or more extensive decomposition, or both. Air flow significantly reduced animal response times only at 500 and 600°C, and appeared to have no significant effect on animal response times at 700 and 800°C. The effect of air flow may be due to more rapid delivery of toxicants to the animals, a higher degree of oxidation, or both.

No unusual effects, such as seizures, were observed in any of the tests, and there were no delayed deaths among the animals surviving the tests. Carbon monoxide appeared to have been the principal toxicant in all cases.

LARGE SCALE TESTS

To more closely simulate actual fire conditions a variety of large scale tests are increasingly used. For example, at General Electric Company's fire test center such testing is done on windows, appliances, public transit seat assemblies, room corners, and on structural form enclosures. To monitor and classify results, the center includes a fire test room and a mobile analytical laboratory housing instruments to measure temperature, combustion gases, and smoke as well as computerized data handling equipment (8-10).

The basic test room is a 14 X 12 ft. room lined with gypsum wallboard, not unlike a room in a typical home or office. Instruments record changes in temperature, gas, and smoke for the duration of the test (Figures 9-10).

Room corner tests are considered a better measure of material fire properties, particularly when the corner is in a room of moderate size where flashover, total room involvement, can be reached. At General Electric, room corner tests are made using two 4-foot by 8-foot sheets of polymer mounted on the walls in the corner of the test room and a 4-foot triangle mounted on the ceiling (Figure 11). The maximum temperatures reached are measured at the ceiling and a 6-foot, 4-foot, and 2-foot heights in the room.

In Table 8 are room corner test results for 60 mil polyetherimide sheet bonded to gypsum wall board. The ignition source was weighed cardboard in a metal waste basket. Temperature and gas concentration maxima were recorded for the three ignition sources used. Polyetherimide sheet showed little involvement and little tendency to spread flame, confirming the intrinsic flame retardancy of polyetherimide resin.

SUMMARY:

Polyetherimide resin therefore is characterized by a unique balance of high performance engineering properties, including flame retardancy. In a variety of tests that have been conducted to date, this unique polymer has exhibited high self-ignition temperatures, low flame spread, high oxygen index and V-O UL-94 rating at 0.060". In addition, the smoke generation is low, and toxic gas evolution is comparable to polycarbonates, with carbon monoxide the principal toxicant. These inherent flame retardancy characteristics combined with the material's high strength and high temperature properties, indicate that polyetherimide is a unique new material, which may find applications in the transportation and construction industries in the future.

ACKNOWLEDGEMENTS:

We particularly thank A. L. Bridgman and H. L. Hess for providing the small scale fire test results. The large scale fire test results were obtained through the work of A. L. Bridgman, H. L. Hess, S. F. Austin and R. A. Simonelli. C. J. Hilado and coworkers provided the animal toxicity test data.

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TABLE 1POLYETHERIMIDE MECHANICAL PROPERTIES

| | <u>ASTM TEST</u> | <u>UNITS</u> | <u>RESULT</u> |
|------------------------------|------------------|--------------|---------------|
| Tensile Strength, Yield | D638 | psi | 15,000 |
| Tensile Modulus | D638 | psi | 430,000 |
| Tensile Elongation, Ultimate | D638 | % | 100 |
| Flexural Strength | D790 | psi | 21,000 |
| Flexural Modulus | D790 | psi | 480,000 |
| Gardner Impact Strength | -- | in. lbs. | >320 |

TABLE 2POLYETHERIMIDE THERMAL PROPERTIES

| | <u>ASTM TEST</u> | <u>UNITS</u> | <u>RESULT</u> |
|---------------------------------|------------------|--------------|---------------|
| Tg | -- | °C | 217 |
| Heat Distortion Temperature | D648 | °C | |
| 264 psi | | | 200 |
| 66 psi | | | 210 |
| Flexural Modulus at Temperature | D790 | psi | |
| 100°C | | | 400,000 |
| 150°C | | | 370,000 |
| 180°C | | | 330,000 |

TABLE 3
POLYETHERIMIDE ELECTRICAL PROPERTIES

| | ASTM Test | Units | 24°C | <u>Results</u> 180°C |
|-----------------------------------|-----------|--------|------------------------|-------------------------|
| Dielectric Constant | D150 | -- | | |
| 60 Hz | | | 3.02 | 2.85 |
| 10 ³ Hz | | | 3.03 | 2.83 |
| 10 ⁵ Hz | | | 3.03 | 2.82 |
| Dissipation Factor | D150 | -- | | |
| 60 Hz | | | .005 | .008 |
| 10 ³ Hz | | | .001 | .002 |
| 10 ⁵ Hz | | | .002 | .003 |
| Dielectric Strength (@ 40 mil) | D149 | | 700 | -- |
| Surface Resistivity | D257 | ohms | 1.0 x 10 ¹⁷ | 1.7 x 10 ¹⁴ |
| Volume Resistivity | D257 | ohm-cm | 2.2 x 10 ¹⁷ | 1.0 x 10 ¹⁵ |

TABLE 4

LABORATORY FIRE PERFORMANCE TEST RESULTS

| | <u>Polyether- imide</u> | <u>Polyether- sulfone</u> | <u>FRPC-I</u> | <u>FRPC-II</u> | <u>PC</u> |
|----------------------------|---------------------------------|-------------------------------|---------------|----------------|-----------|
| | (Nominal 0.060 Thickness) | | | | |
| <u>IGNITION</u> | | | | | |
| D1929 (Setchkin apparatus) | | | | | |
| Self °C | 535 | 560 | 477 | 480 | 505 |
| Flash °C | 520 | 560 | 425 | 375 | 450 |
| UL-94 | V-0 | V-0 | V-0 | V-0 | - |
| FAR 25.853a (F501) | | | | | |
| Flame-out-time (seconds) | 2.1 | 0 | 4 | 6.2 | - |
| Burn length (inches) | 1.7 | 0.5 | 3.9 | 3.3 | - |
| <u>FLAME SPREAD</u> | | | | | |
| El62 (Radiant Panel) | | | | | |
| F _s | 1.1 | 2.2 | 7 | 5.4 | 5.7 |
| Q | 2.4 | 2.4 | 11 | 2.9 | 9.8 |
| I _s | 2.7 | 5.4 | 81 | 17 | 56 |
| <u>EASE OF EXTINCTION</u> | | | | | |
| D2863 | | | | | |
| Oxygen Index | 47 | 37 | 37 | 33 | 25 |
| <u>SMOKE</u> | | | | | |
| D2843 | | | | | |
| XP-2 Smoke Chamber | 28 | 24 | 71 | 87 | 62 |
| E-662 | | | | | |
| NBS Smoke Chamber | | | | | |
| D _S (1.5 min.) | 0 ^a 0 ^b | 0 0 | 4.7 0 | 4 0 | 13 .1 |
| D _S (4 min.) | 0.7 0 | 1.7 0 | 60 0.1 | 74 .3 | 127 1.2 |
| D _{max} | 31 .4 | 37 .6 | 152 7 | 199 12 | 130 4 |
| (a. Flaming condition) | | | | | |
| (b. Smoldering condition) | | | | | |

Note: ASTM Test designation given where appropriate.

FRPC-I, FRPC-II, and PC refer to flame retardant grades and natural polycarbonate respectively.

TABLE 5
 COMPARISON OF ENGINEERING PLASTICS
 TIME TO DEATH, IN MINUTES
USF-NASA TOXICITY SCREENING TEST METHOD

| Test Conditions | 1 polyoxy- methylene | 2 polyether- sulfone | 3 polyether- imide | 4 poly- carbonate | 5 Douglas fir |
|---------------------------|----------------------------|----------------------------|--------------------------|-------------------------|---------------------|
| <u>No Forced Air Flow</u> | | | | | |
| 200-800°C rising | 10.7±0.9 | 12.4±1.2 | 17.4±0.3 | 21.8±2.2 | 14.8±0.9 |
| 200°C fixed | | | n.d. | n.d. | n.d. |
| 300°C fixed | | n.d. | n.d. | | 28.8±0.9 |
| 400°C fixed | 11.0±1.0 | n.d. | n.d. | n.d. | 20.2±2.7 |
| 500°C fixed | 7.0±0.6 | 34.0±23.8 | 26.3±2.0 | 23.0±2.2 | 11.8±0.5 |
| 600°C fixed | 3.6±0.2 | 6.0±0.4 | 10.4±1.5 | 18.5±3.3 | 8.0±0.9 |
| 700°C fixed | 2.5±0.1 | 4.4±0.4 | 5.9±0.2 | 12.0±0.1 | 5.8±1.1 |
| 800°C fixed | 2.6±0.2 | 5.0±0.8 | 4.7±0.1 | 9.1±2.0 | 4.6±0.9 |
| <u>1 L/min Air Flow</u> | | | | | |
| 200-800°C rising | 10.2±0.1 | | 16.8±0.7 | | 11.7±0.4 |
| 200°C fixed | | | n.d. | | n.d. |
| 300°C fixed | | | n.d. | | 17.5±3.7 |
| 400°C fixed | 8.3±0.8 | n.d. | n.d. | n.d. | 10.2±0.6 |
| 500°C fixed | 4.7±0.3 | 18.0±2.2 | 17.5±4.7 | 10.1±1.7 | 4.8±0.1 |
| 600°C fixed | 3.5±0.5 | 5.6±0.7 | 6.9±0.1 | 6.9±0.8 | 3.8±0.1 |
| 700°C fixed | 2.4±0.2 | 4.1±0.2 | 7.8±3.0 | 5.9±0.6 | 3.5±0.3 |
| 800°C fixed | 2.3±0.4 | 3.4±0.1 | 4.2±0.3 | 5.7±0.6 | 2.6±0.1 |

n.d. = no deaths

TABLE 6

TOXICITY OF PYROLYSIS GASES FROM POLYETHERIMIDE:

USF-NASA METHOD, NO FORCED AIR FLOW

| Temperature Program, °C | Weight Charged | Weight Pyrolyzed | Time To Staggering Min. | Time To Convulsions Min. | Time To Collapse Min. | Time To Death Min. | CO Conc. PPM |
|-------------------------|----------------|------------------|-------------------------|--------------------------|-----------------------|--------------------|---------------------|
| 200-800 Rising | 1.00277 | 0.44105 | | 15.3±0.5 | 15.7±0.5 | 17.4±0.3 | 7,800 |
| 800 Fixed | 1.00250 | 0.52370 | | 3.8±0.1 | 4.2±0.1 | 4.7±0.1 | 12,000 ² |
| 700 Fixed | 1.00284 | 0.50184 | | 4.7±0.4 | 5.0±0.5 | 5.9±0.2 | 10,600 |
| 600 Fixed | 1.00000 | 0.44358 | 7.0±0.5 | 7.4±0.7 | 8.1±1.2 | 10.4±1.5 | 7,800 |
| 500 Fixed | 0.99911 | 0.27906 | 17.1±3.1 | 18.9±2.5 | 20.8±1.5 | 26.3±2.0 | 5,800 |
| 400 Fixed | 1.00013 | 0.02090 | | | | n.d. | 0 |
| 300 Fixed | 1.00102 | 0.00845 | | | | n.d. | 0 |
| 200 Fixed | 1.00092 | 0.00458 | | | | n.d. | 0 |

n.d. = no deaths

TABLE 7
TOXICITY OF PYROLYSIS GASES FROM POLYETHERIMIDE:

USF-NASA METHOD, NOMINAL 1 L/MIN AIR FLOW

| Temperature Program, °C | Weight Charged g | Weight Pyrolyzed g | Time To Staggering Min. | Time To Convulsions Min. | Time To Collapse Min. | Time To Death Min. | CO Conc. PPM |
|----------------------------|------------------------|--------------------------|-------------------------------|--------------------------------|-----------------------------|--------------------------|---------------------|
| 200-800 Rising | 1.00021 | 0.60914 | | 14.1+0.2 | 14.4+0.2 | 16.8+0.7 | 5,900 ²⁸ |
| 800 Fixed | 0.99906 | 0.63019 | | 3.0+0.1 | 3.3+0.1 | 4.2+0.3 | 8,500 ³ |
| 700 Fixed | 1.00378 | 0.72178 | | 3.8+0.0 | 4.7+0.6 | 7.8+3.0 | 4,100 |
| 600 Fixed | 1.00026 | 0.49877 | | 5.8+0.1 | 6.0+0.1 | 6.9+0.1 | 14,400 |
| 500 Fixed | 1.00178 | 0.48940 | 13.2 | 15.3+5.4 | 15.5+5.0 | 17.5+4.7 | 9,300 |
| 400 Fixed | 1.00159 | 0.01964 | | | | n.d. | 0 |
| 300 Fixed | 1.00225 | 0.00928 | | | | n.d. | 0 |
| 200 Fixed | 1.00206 | 0.00522 | | | | n.d. | 0 |

n.d. = no deaths

TABLE 8

ROOM CORNER TESTS (NOMINAL 0.060 THICKNESS)
(SOURCE - CARDBOARD IN METAL WASTEBASKET)

| | FIRE SOURCE (lbs) | MAXIMUM TEMPERATURES Ceiling 6' 4' | °C | MAXIMUM CO (ppm) | CO ₂ (%) | SMOKE O.D. | MAXIMUM HYDROCARBONS % LEL | MINI- MUM O ₂ % | |
|----------------|-------------------------|--|-----|---------------------|---------------------|------------|----------------------------------|----------------------------------|------|
| POLYETHERIMIDE | 3# | 146 | 88 | 53 | 140 | 1.5 | 0.23 | 3.3 | 19.5 |
| BLANK | 3# | 129 | 80 | 46 | 107 | 1.3 | 0.12 | 2.3 | 19.5 |
| POLYETHERIMIDE | 6# | 152 | 95 | 55 | 181 | 1.5 | 0.06 | 4.2 | 19.3 |
| BLANK | 6# | 155 | 97 | 54 | 115 | 1.7 | 0.21 | 2.2 | 19.3 |
| POLYETHERIMIDE | 10# | 289 | 206 | 108 | 689 | 3.9 | 0.36 | 7.2 | 16.2 |
| BLANK | 10# | 240 | 150 | 71 | 225 | 3.0 | 0.27 | 3.6 | 17.7 |

FIGURE 1
POLYETHERIMIDE: GENERAL STRUCTURE

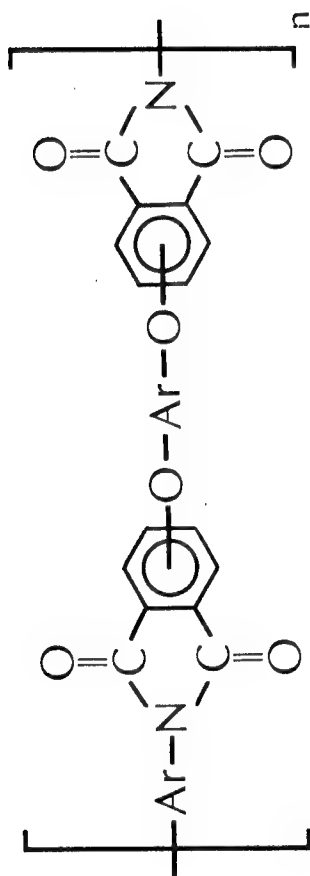


FIGURE 2
POLYETHERIMIDE MELT VISCOSITY

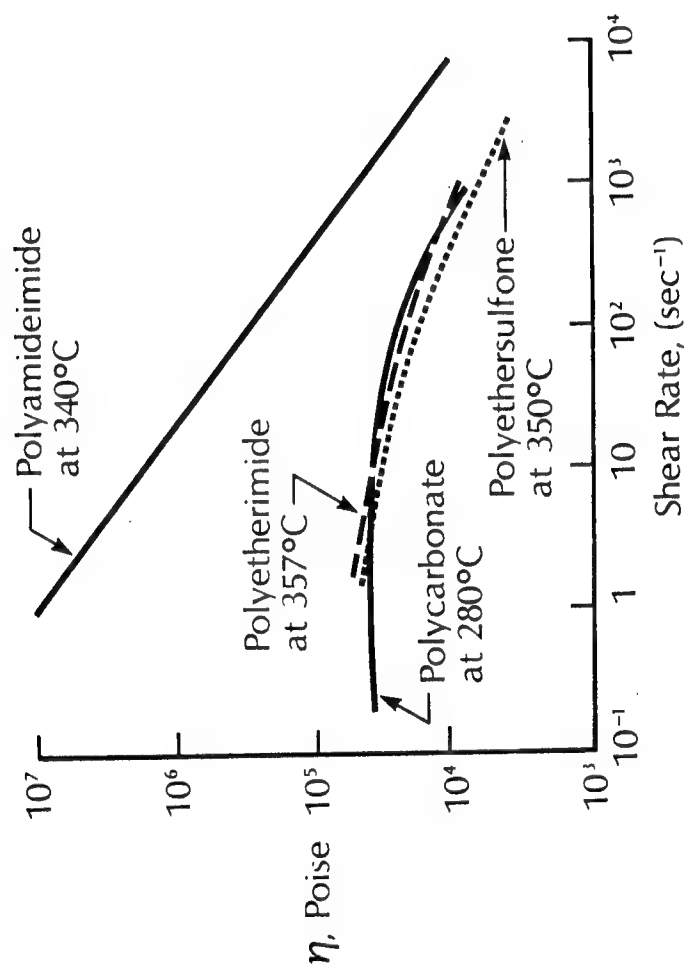


FIGURE 3

RADIANT PANEL TEST APPARATUS

(ASTM E 162)

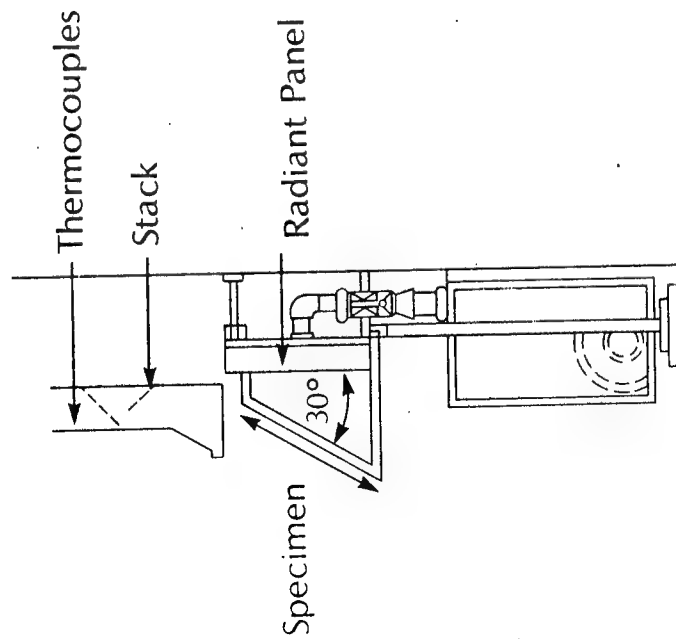


FIGURE 4

OXYGEN INDEX APPARATUS

(ASTM D 2863)

Glass Column

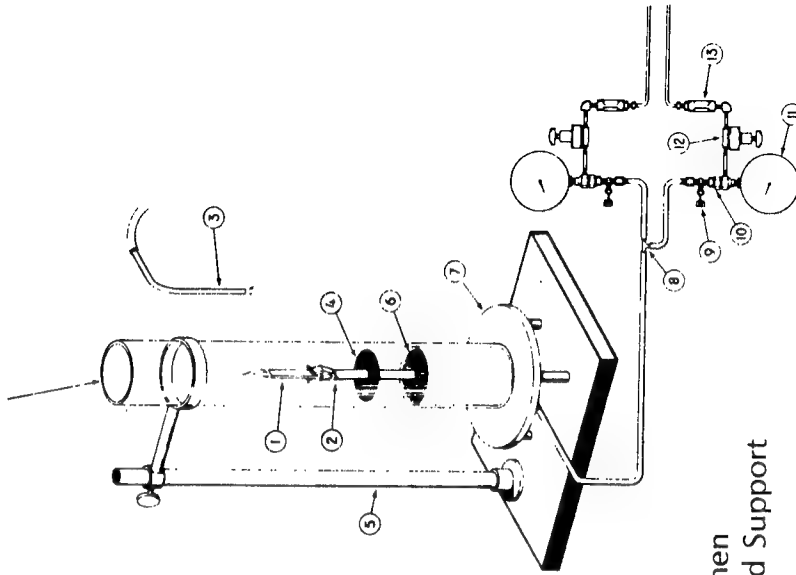
(Minimum Dimension 45cm H. \times 7.5cm I.D.)

FIGURE 5

COMPARISON OF UL-94 AND OXYGEN INDEX DATA FOR 152 PLASTICS. NON-FLAME RETARDANT (HB RATED) MATERIALS HAVE OXYGEN INDICES CENTERED AT 20; V-2 MATERIALS AT 26, V-1 MATERIALS AT 28, V-0 MATERIALS AT 29.

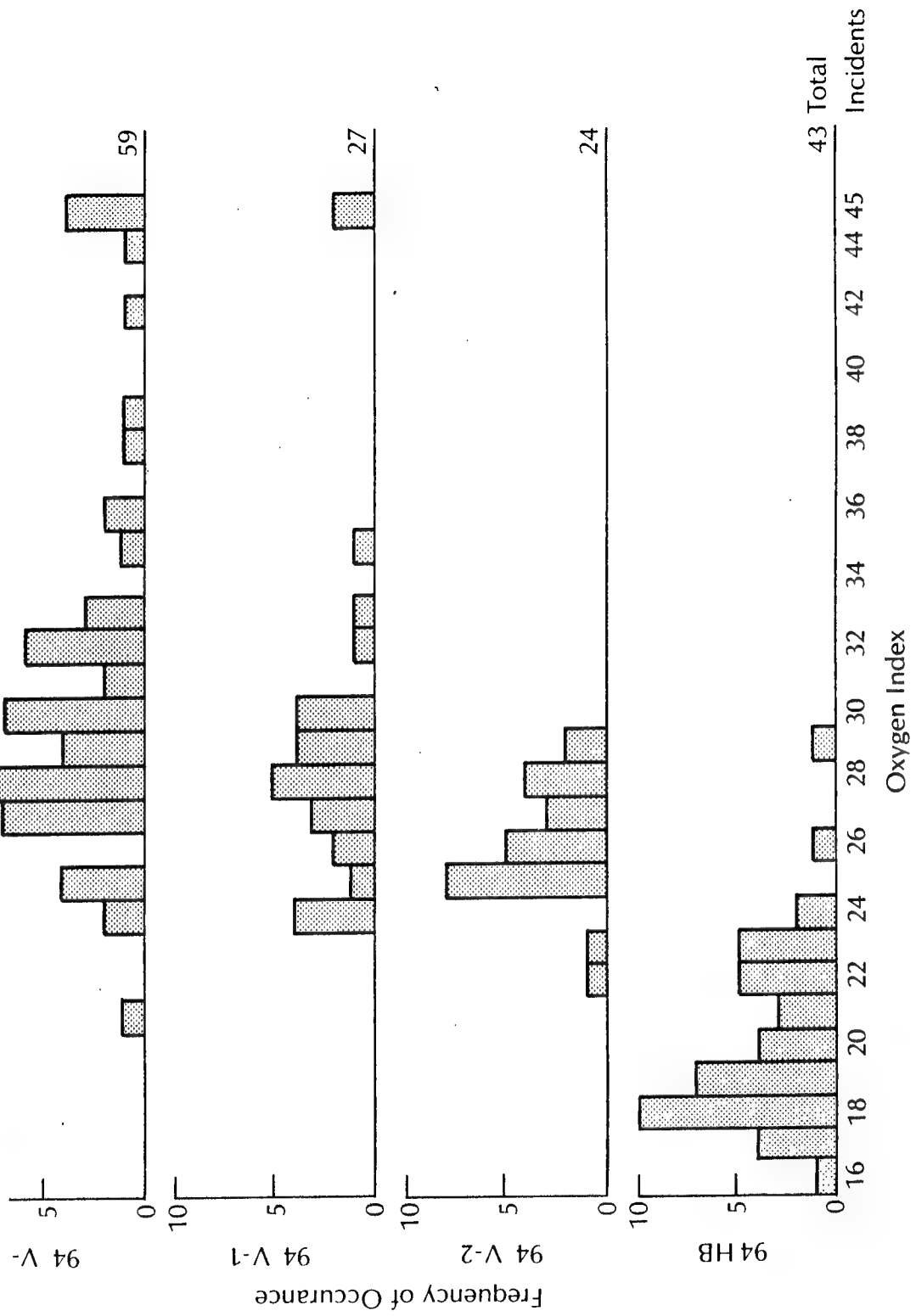


FIGURE 7

NBS SMOKE CHAMBER (ASTM E 662)

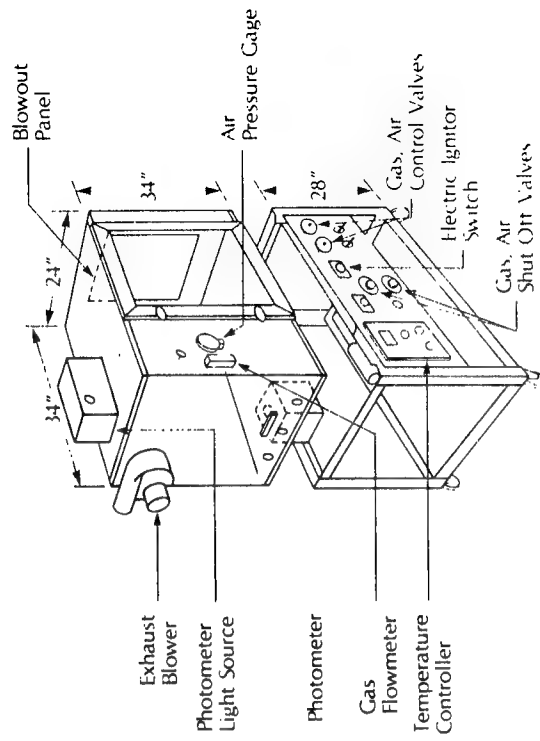


FIGURE 6

XP-2 SMOKE CHAMBER (ASTM D2843)

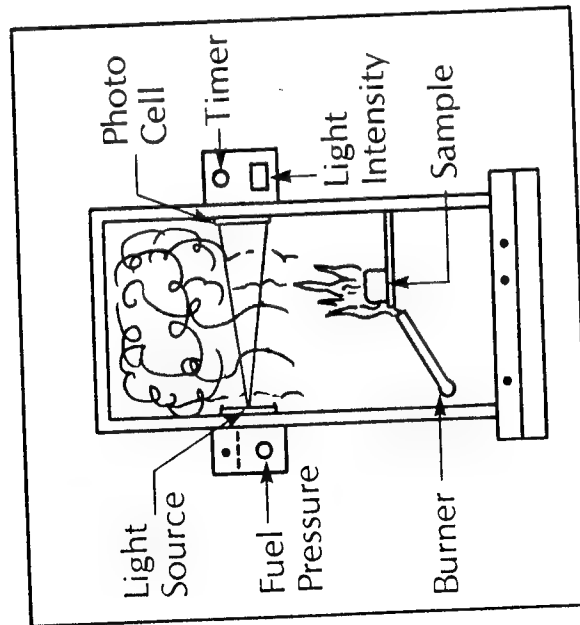


FIGURE 8
ANIMAL EXPOSURE CHAMBER
USF-NASA METHOD

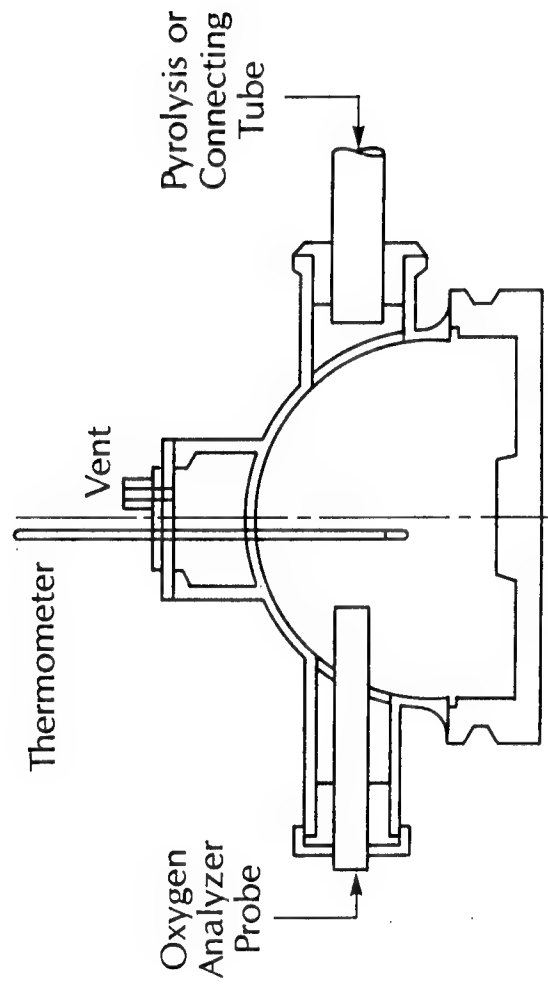


FIGURE 9

FIRE TEST CENTER AT MT. VERNON, INDIANA. THE CENTER INCLUDES A FIRE TEST ROOM, CENTER; A MOBILE ANALYTICAL LABORATORY LEFT; AND A STORAGE BUILDING. SINCE REAL FIRE BEHAVIOR IS SENSITIVE TO WEATHER, A WEATHER STATION IS INCLUDED AS PART OF THE INSTRUMENTATION.



FIGURE 10

INTERIOR OF MOBILE ANALYTICAL LABORATORY SHOWING GAS INFRARED ANALYZERS AT LEFT AND COMPUTER TERMINAL AT RIGHT. CONSIDERABLE INSTRUMENTATION ALLOWS MEASUREMENT OF TEMPERATURE, SMOKE AND GAS PROFILES VERSUS TIME FOR EACH LARGE SCALE FIRE TEST.

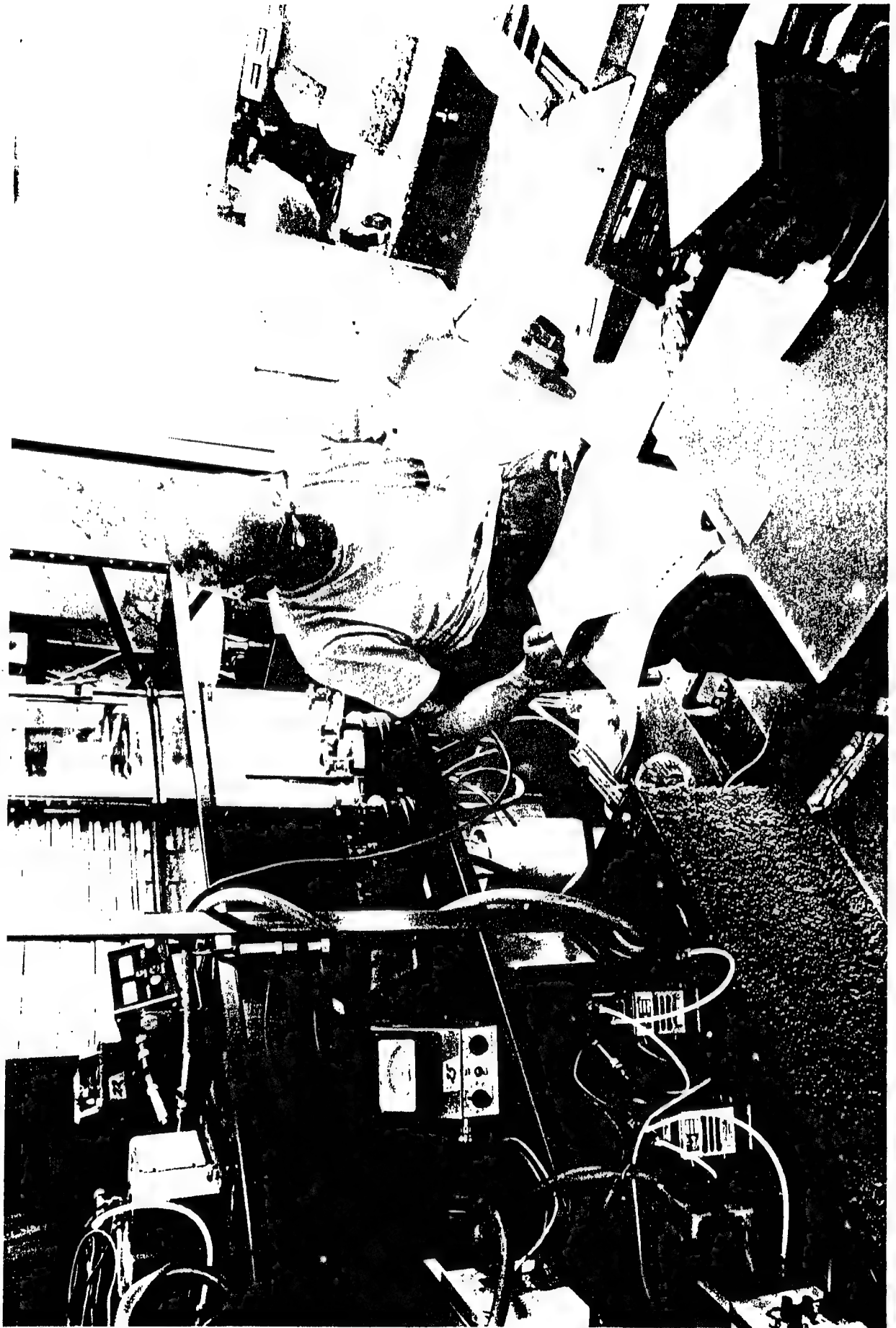
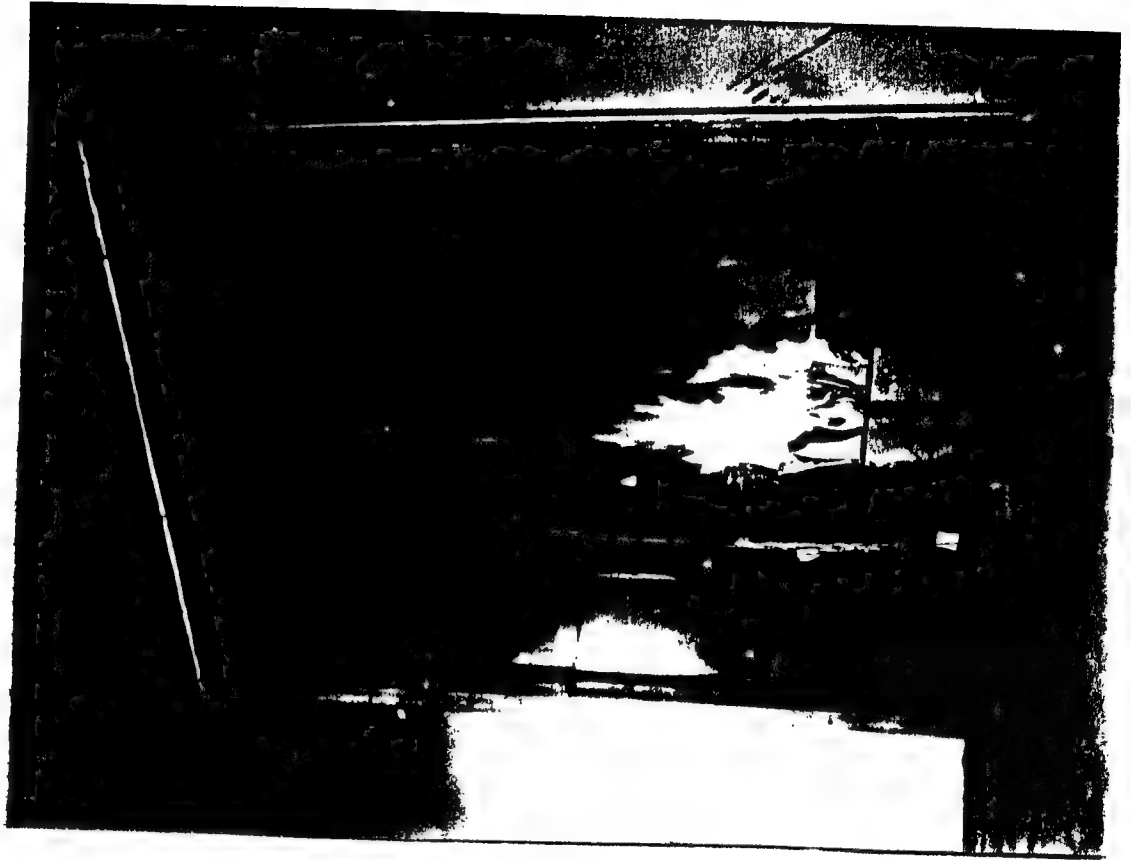


FIGURE 11

IN THE ROOM CORNER TEST, TWO 4-FOOT BY 8-FOOT SHEETS ARE MOUNTED ON THE WALLS AND A 4-FOOT BY 4-FOOT TRIANGLE IS MOUNTED ON THE CEILING. THE IGNITION SOURCE IS CARDBOARD IN A METAL WASTEBASKET. THERMO-COUPLES AND GAS SAMPLING LINES ARE VISIBLE IN THE PHOTOGRAPH.



THE FIRE AND SMOKE PROPERTIES OF CABLES
FOR USE IN AIR HANDLING SYSTEMS

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Abstract

Fire and smoke performance objectives for exposed installation of communications cables in air handling spaces were added to the 1975 National Electrical Code. A test was developed for flame and smoke measurement of cables. Tests were conducted and, based upon comparison of performance to acceptable wiring systems, several low smoke and flame spread cables were classified by UL.

Introduction

The National Electrical Code (NFPA No. 70) restricts the types of wiring permitted in air handling spaces in order to limit the spread of fire and smoke. All cables installed in the return air space above a suspended ceiling, often called a plenum, must be enclosed in metallic raceway or conduit.¹ Alternately, specified metal sheathed cables¹ may be installed without conduit. Exceptions to the conduit requirement are provided for communications,² power-limited,³ and fire alarm cables⁴ that are listed as having "adequate fire resistance and low-smoke producing characteristics."

The three types of metal sheathed cables permitted are mineral-insulated metal-sheathed (Type MI⁵), metal-clad (Type MC⁶), and armored (Type AC⁷). Acceptance of these metal sheathed cables is presumed to be based on their similarity to a conduit system. The constructions of these cables are specified in the Code and in the Underwriters Laboratories (UL) Listing requirements. For exposed wiring other than the specified metal sheathed cables, the Code does not provide construction details. Instead it specifies a performance requirement that the cables must have adequate fire resistant and low smoke producing characteristics.

When this performance requirement was first incorporated in the 1975 Code, an appropriate test for assessing smoke and fire resistance did not exist. The Code writers did not know that it would be possible to develop cables to meet the Code intent. Their purpose in adopting a performance requirement was to encourage innovation in the development of highly fire resistant and low smoke producing cables.

In response to the performance criteria in the Code, a test method was developed for measuring flame spread and smoke properties of cable,⁸ and highly fire resistant and low smoke producing cables are now available. These cables are Classified by UL as meeting the intent of the Code.^{9,10} The fire testing leading to the Classifications is the subject of this paper.

Experimental Plan

Fire experience has shown that enclosing cables in metallic conduit adequately limits the spread of fire and smoke from the cables within. Therefore, testing was conducted to compare flame spread and smoke from conventional cable enclosed in conduit with that from a new generation of highly fire resistant and low smoke producing cables. The new cables were judged to have "adequate fire-resistant and low-smoke producing characteristics" if, when tested without conduit, their flame spread and smoke production were less than or comparable to conventional cable in conduit.

Test Method

The test was developed and described by Beyreis et al.⁸ The test method utilizes the Steiner Tunnel (Figure 1). A single layer of cable or conduit is installed in a cable rack as shown schematically in Figure 2. The fire test is conducted with a 300,000 BTU/hour diffusion flame ignition source which engulfs the first 4-1/2 feet of cable rack for the 20 minute test duration. Air movement through the tunnel, controlled at 240 ft/min, exhausts combustion products while providing air for combustion.

The relationship between flame propagation in this test and flame propagation in a simulated plenum has been investigated.^{11,12} It was concluded¹² that this test provides a severe fire environment in comparison to the fire in a simulated plenum. Therefore this test is a useful and conservative tool for judging the flame spread and smoke producing properties of cables.

Smoke is measured in the tunnel by means of a photocell and light source mounted across the 16 inch diameter exhaust duct. Optical density of the smoke is recorded during each test. Optical density is defined as $\log_{10} (I_0/I)$ where I_0 is the incident light intensity and I is the light intensity which reaches the photocell after attenuation by smoke. Smoke which attenuates 90% of the incident light yields an optical density value of 1, 99% attenuation yields 2, and 99.9% attenuation equals 3. Optical density is used because it is linearly related to human visibility¹³ and directly proportional to the concentration of smoke particles.¹⁴

Cables and Conduit Tested

Four different types of cable were tested; 1) telephone inside wiring cable, 2) telephone station wire, 3) power limited signal/fire alarm cable, and 4) coaxial cable. Two versions of each cable type were tested, conventional and highly fire resistant. The conventional cables were jacketed with PVC and insulated with either PVC or polyethylene (PE). The highly fire resistant cables were all insulated and jacketed with a fluorinated ethylene propylene copolymer (FEP). Further details of the cable constructions are given in Table I and Figure 3.

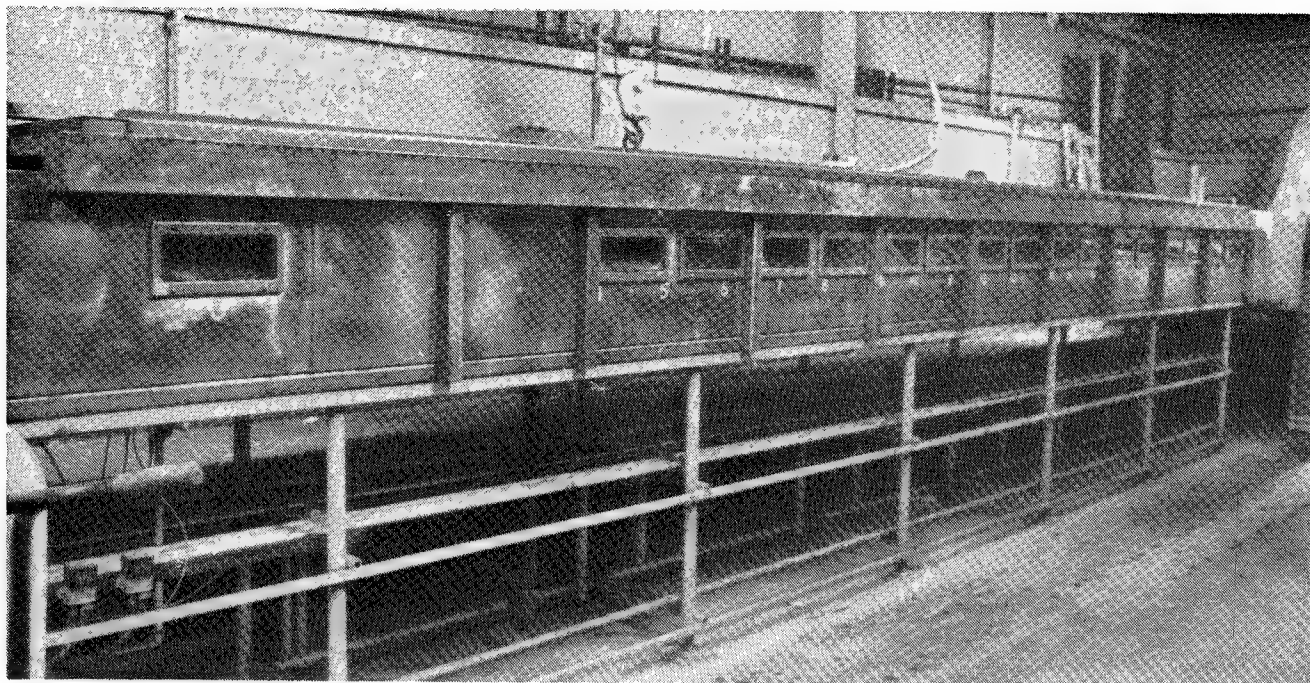


Figure 1. The Steiner Tunnel

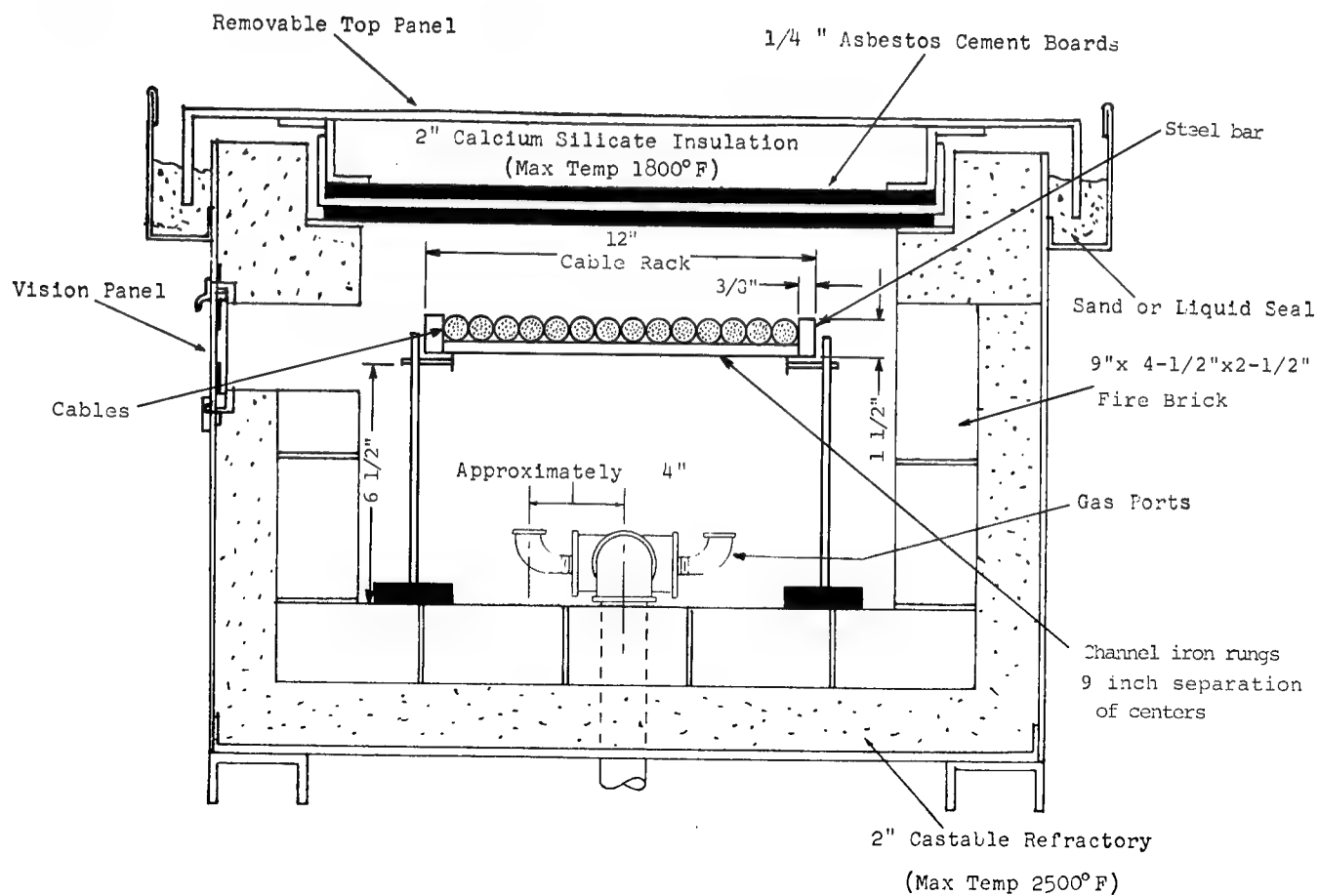
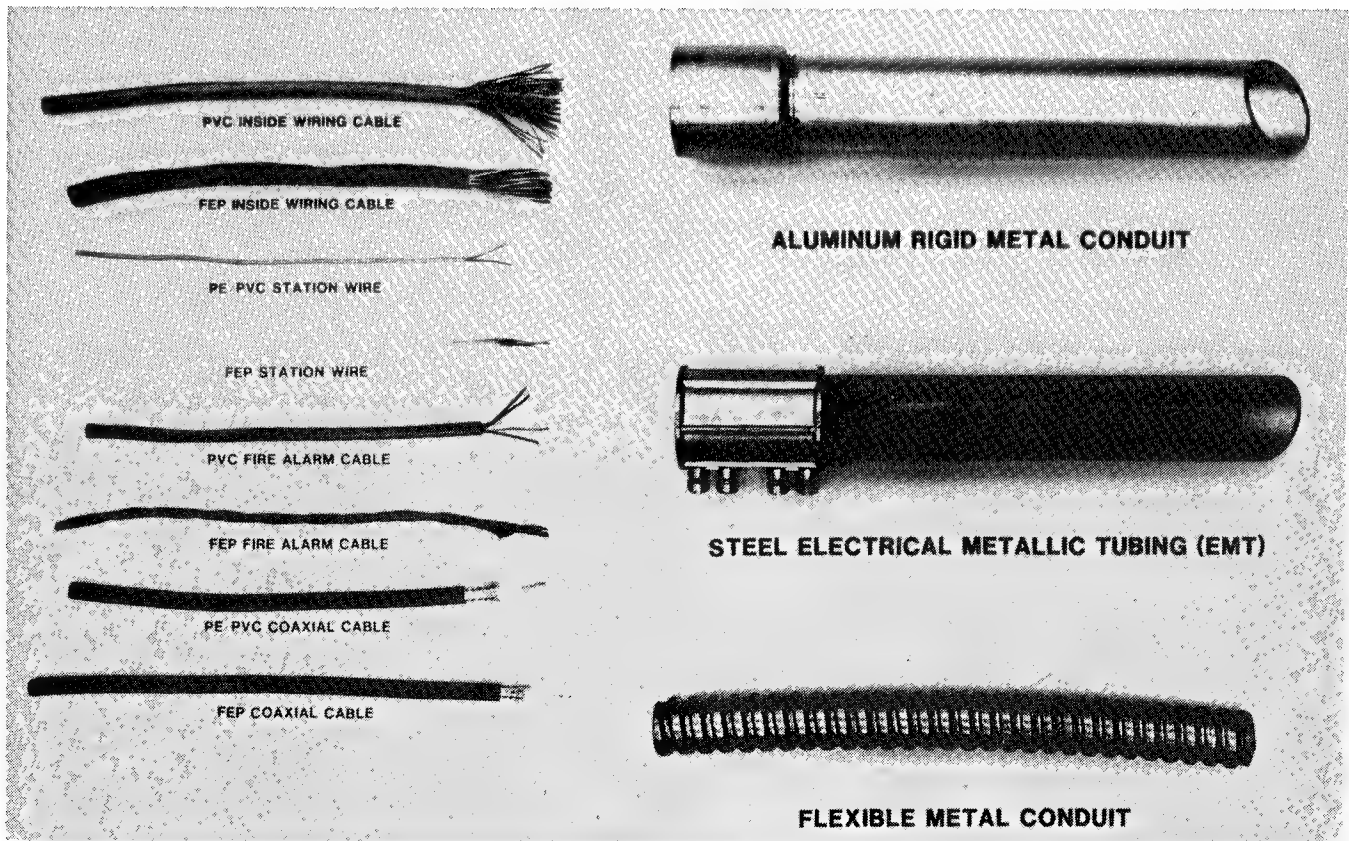


Figure 2. Cross Section of Tunnel Showing Mounting of Cable Rack

TABLE I
Cables Tested

| <u>Cable Type</u> | <u>AWG</u> | <u>Construction</u> | <u>Insulation Material</u> | <u>Jacket Material</u> |
|---------------------|------------|---------------------|----------------------------|------------------------|
| Inside Wiring Cable | 24 | 25 pairs | PVC | PVC |
| Inside Wiring Cable | 22 | 25 pairs | FEP | FEP |
| Station Wire | 22 | 4 wire quad | polyethylene | PVC |
| Station Wire | 22 | 4 wire quad | FEP | FEP |
| Fire Alarm | 18 | 6 conductors | PVC | PVC |
| Fire Alarm | 18 | 6 conductors | FEP | FEP |
| Coaxial | | RG-8 single | foamed polyethylene | PVC |
| Coaxial | | RG-8 single | foamed FEP | FEP |



Four different types of conduit were used (Figure 4); 1) aluminum rigid metal conduit with threaded aluminum connectors, 2) steel electrical metallic tubing (EMT) with die cast setscrew connectors, 3) steel flexible metal conduit, without connectors, and 4) aluminum flexible metal conduit, without connectors.

Results

Telephone Cable

Twenty-five pair inside wiring cable is the most commonly used cable for key telephone sets. Therefore, it was tested in several different types of conduit. Figure 5 shows flame spread versus time curves for two tests of 25 pair inside wiring cable in aluminum rigid metal conduit. The cable rack was filled with 6 lengths of 1-1/4" conduit, each containing 3 lengths of 25 pair cable. In both tests the peak flame spread was very low - only 2 feet. Smoke from one of the tests is shown in Figure 6. Smoke production was very low; optical density, averaged over the 20 minute test period was only 0.05, with a peak optical density of 0.2

Results for cable in steel electrical metallic tubing (EMT) are similar. Peak flame spread for 6 lengths of 1-1/4" steel EMT each containing 3 twenty-five pair cables, is only 2-1/2 feet (Figure 7). Smoke results for one test are shown in Figure 8. Average optical density for the two tests was 0.08, with a peak of 0.38 in one of the tests.

Flame spread versus time curves for 10 lengths of 3/4" steel or aluminum flexible metal conduit each containing one 25 pair cable are shown in Figure 9 (steel) and Figure 10 (aluminum). Peak flame spreads for cable in either conduit were only 2 to 2-1/2 feet. Smoke was negligible for cable in the steel conduit (Figure 11); average optical density for the duplicate tests was 0.007 with a peak of 0.06 in one of the tests. Cable in aluminum conduit emitted very little smoke, (Figure 12) but considerably more than cable in steel conduit; average optical density for the duplicate tests was 0.07, with a peak of 0.56 in one test.

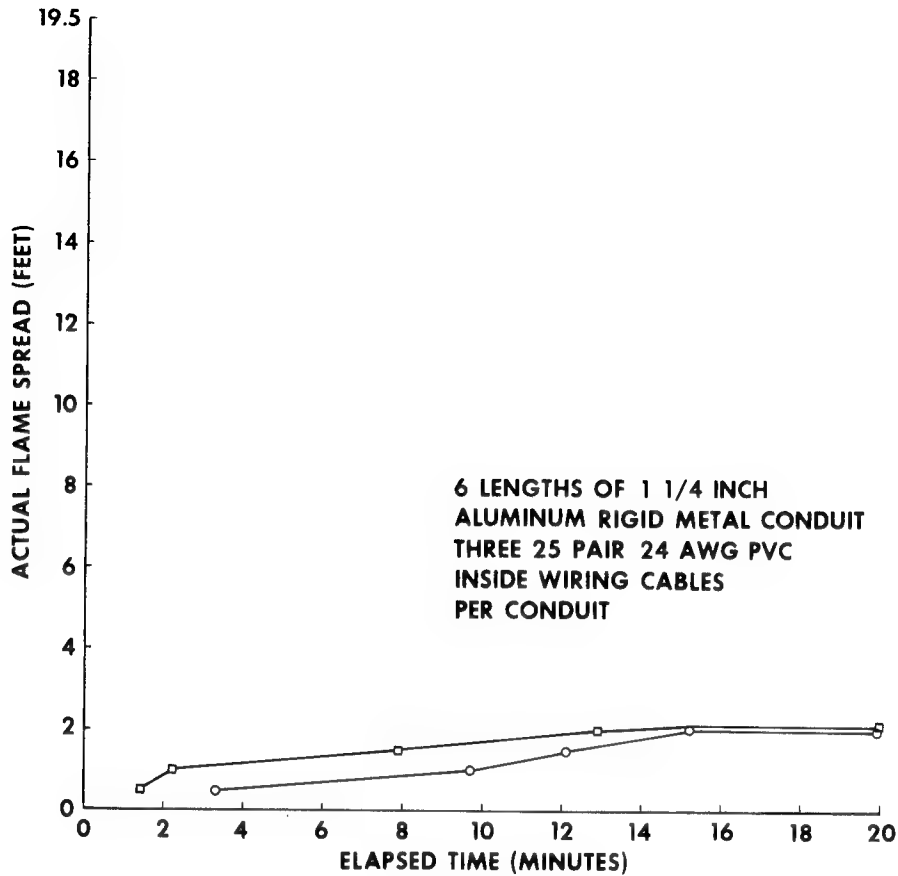


FIGURE 5

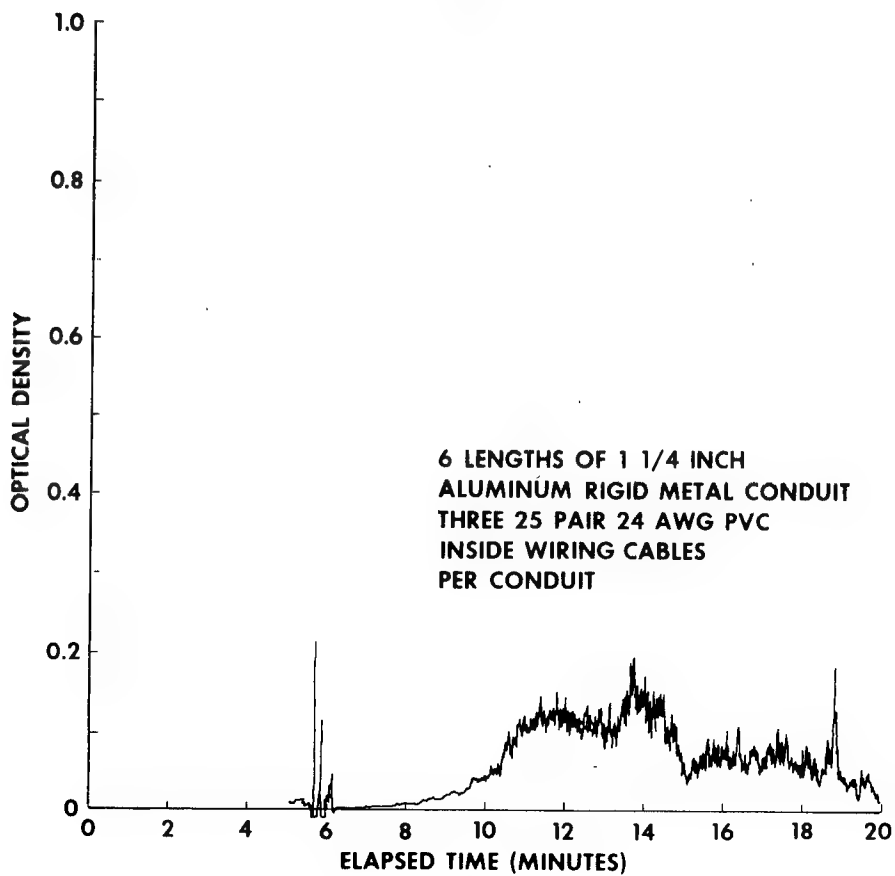


FIGURE 6

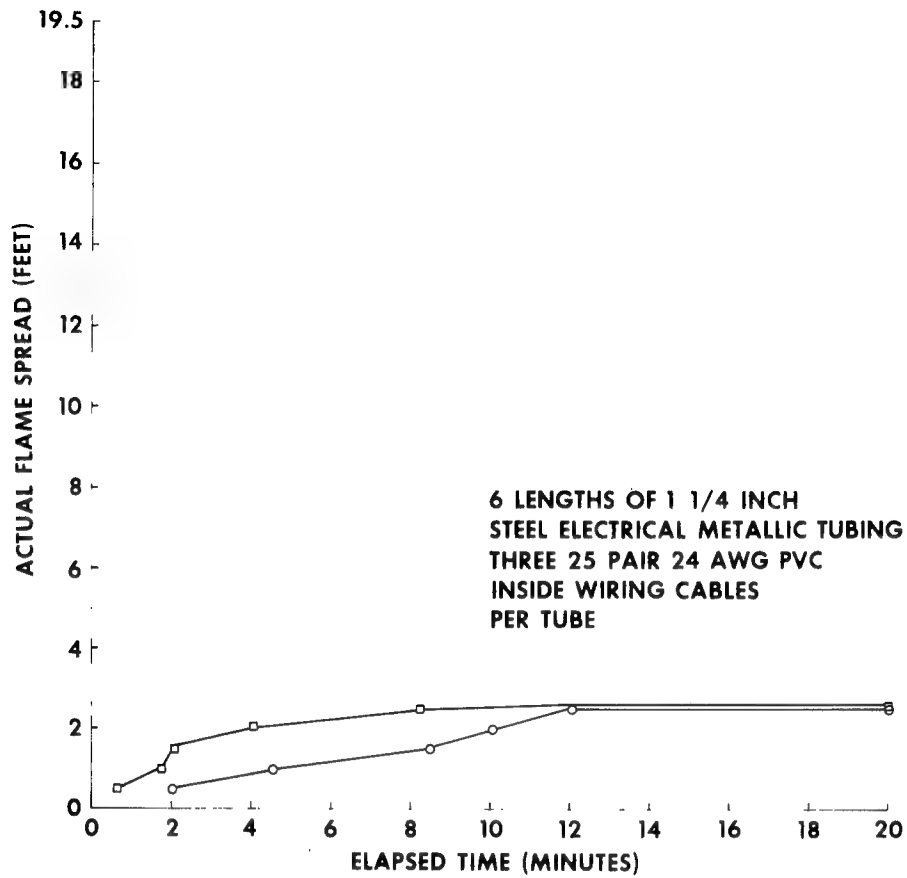


FIGURE 7

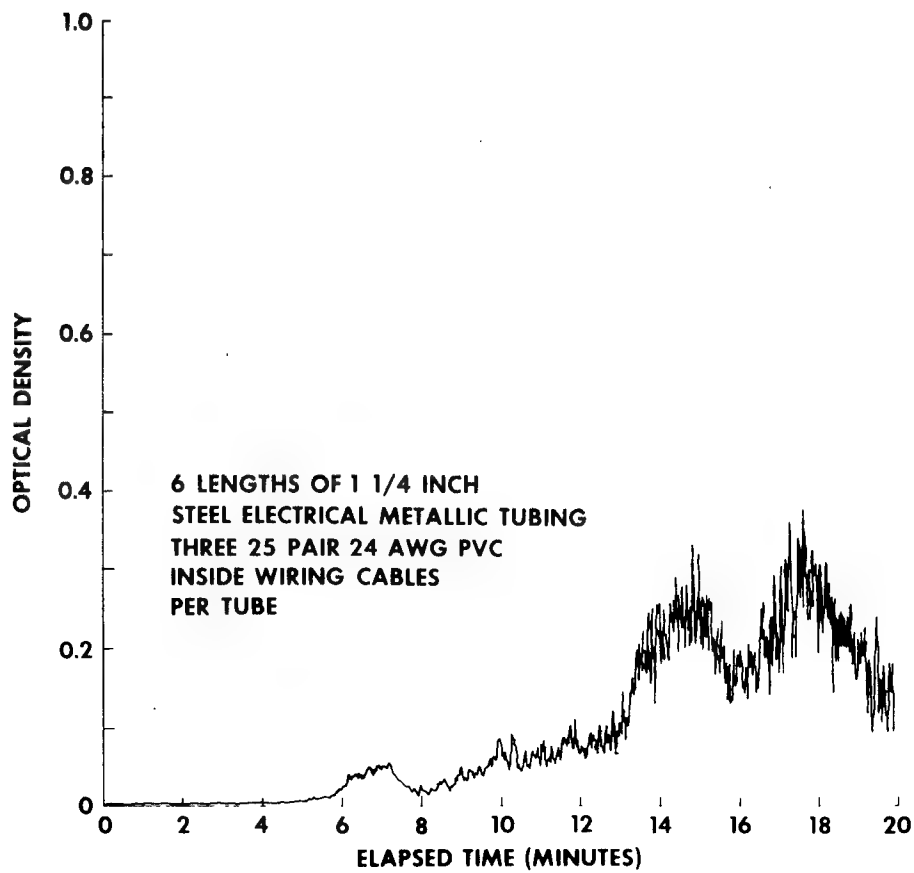


FIGURE 8

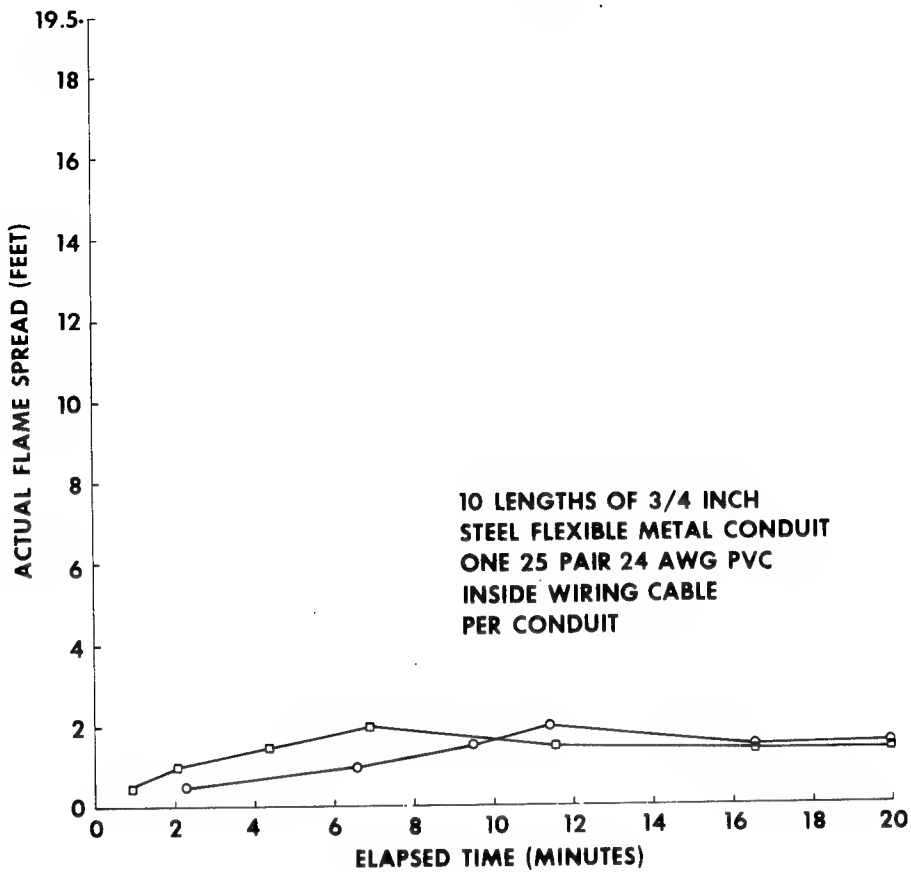


FIGURE 9

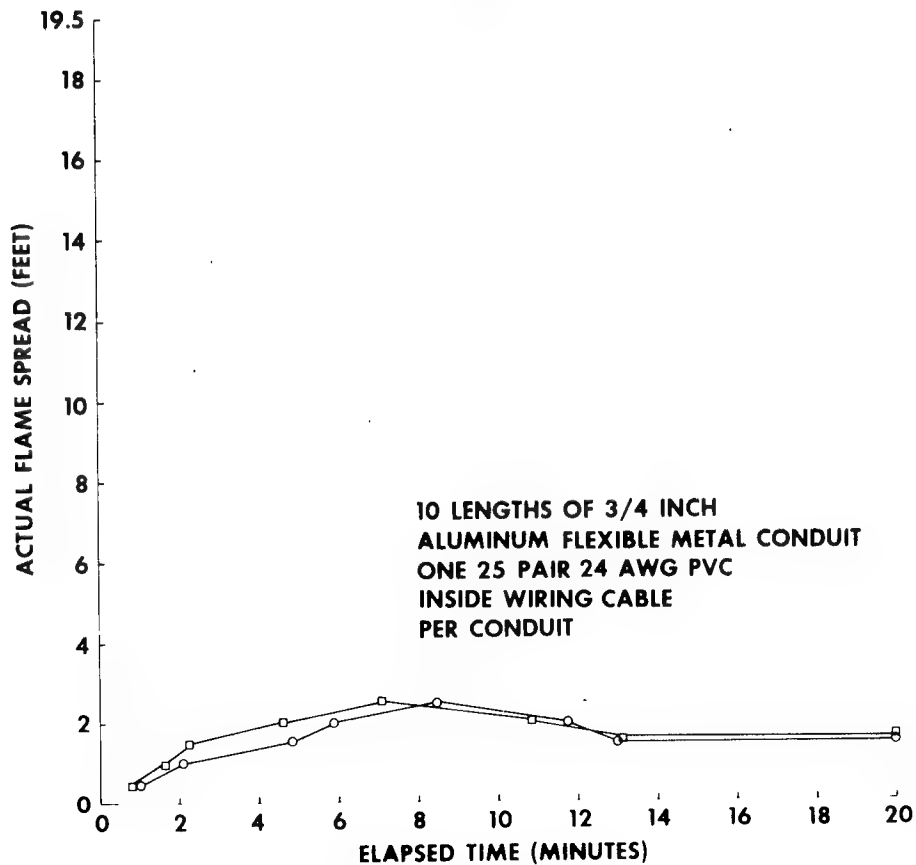


FIGURE 10

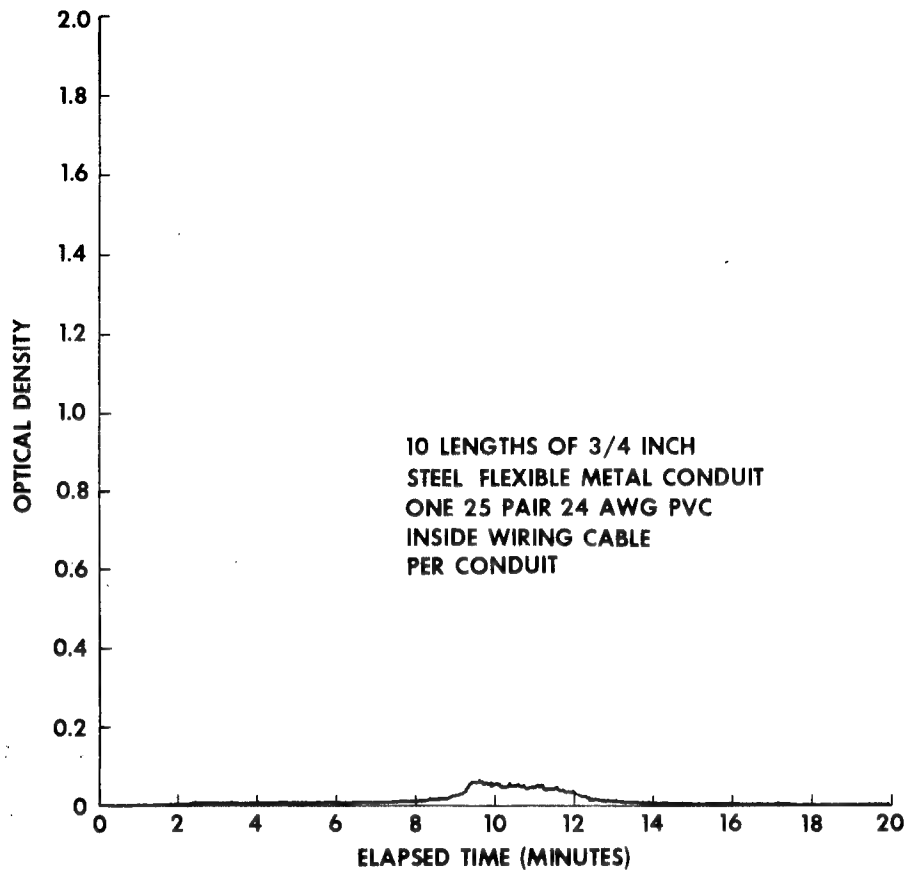


FIGURE 11

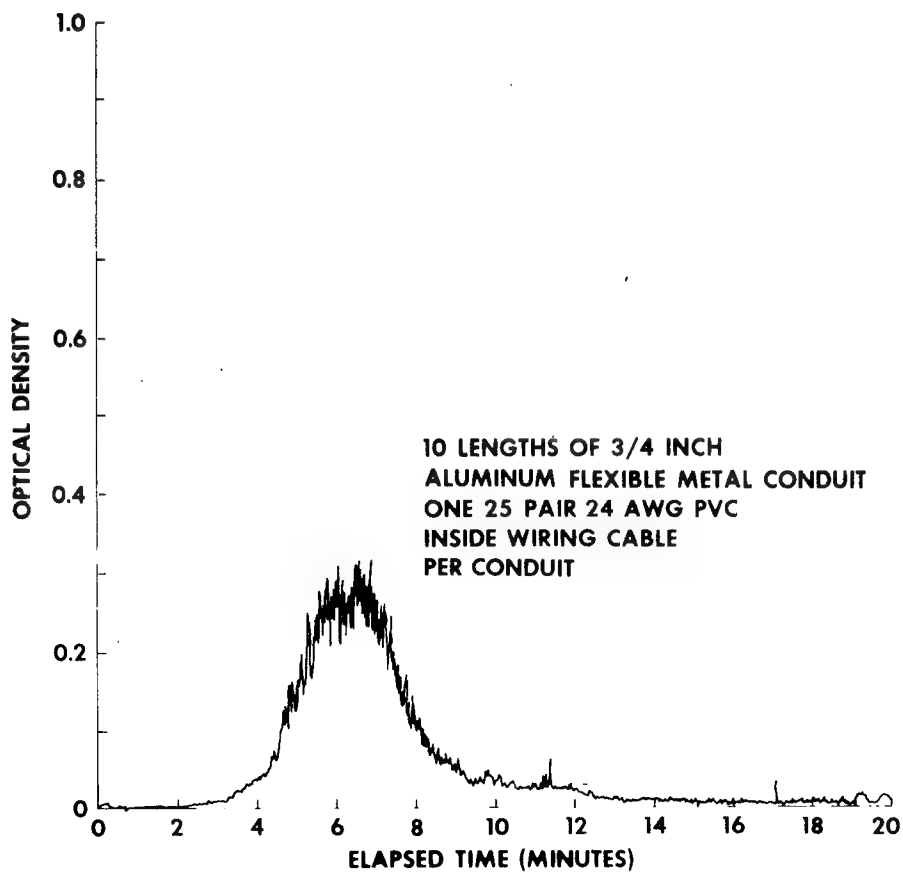


FIGURE 12

Flame spread versus time curves for 18 lengths of 22 gauge, 25 pair FEP telephone cable are shown in Figure 13. The peak flame spread for both tests was 3 feet. Smoke was low (Figure 14). Average optical density for the duplicate tests was 0.08, with a peak at 0.35 in one test, (Figure 14). The total amount of smoke emitted, as measured by the average optical density, is similar to the smoke emitted by conventional cable in steel EMT.

Figure 15 shows flame spread versus time curves of two tests of quadded PE/PVC station wire in 3/4" aluminum flexible conduit. Ten lengths of conduit each containing seven lengths of cable, were tested. The peak flame spread was 3.5 feet. Considerable smoke was emitted (Figure 16); average optical density for the two tests was 0.2, with a peak of 0.85 in one test.

Seventy lengths of FEP insulated and jacketed station wire was run in triplicate and had a peak flame spread of 3.5 feet (Figure 17). Smoke was low (Figure 18). Average optical density for one test was 0.07 with a peak of 0.08 in two of the tests. Thus, the smoke emitted was less than the smoke from conventional station wire in conduit.

Fire Alarm Cable

Flame spread versus time curves for 6 lengths of 1-1/4" steel electrical metallic tubing (EMT) each containing 5 lengths of fire alarm cable are shown in Figure 19. Peak flame spreads were 4 and 3-1/2 feet. Smoke results are shown in Figure 20; average optical density was 0.13, with a peak of 0.70 in one test.

Twelve lengths of 1/2" aluminum flexible metal conduit, each containing one length of fire alarm cable, were tested. Peak flame spreads of 5-1/2 feet and 6 feet were obtained (Figure 21). Smoke results from one test are shown in Figure 22; average smoke for both tests was 0.21, with a peak of 1.20 in one test.

The flame spread versus time curves for 36 lengths of FEP fire alarm cable show a maximum flame spread of 3 feet (Figure 23). Figure 24 shows the smoke emitted was low. Average optical density for the two tests was 0.04, with a peak at 0.15 in each test. Thus the smoke produced was less than the smoke from conventional cable in conduit even though more lengths of FEP cable were tested.

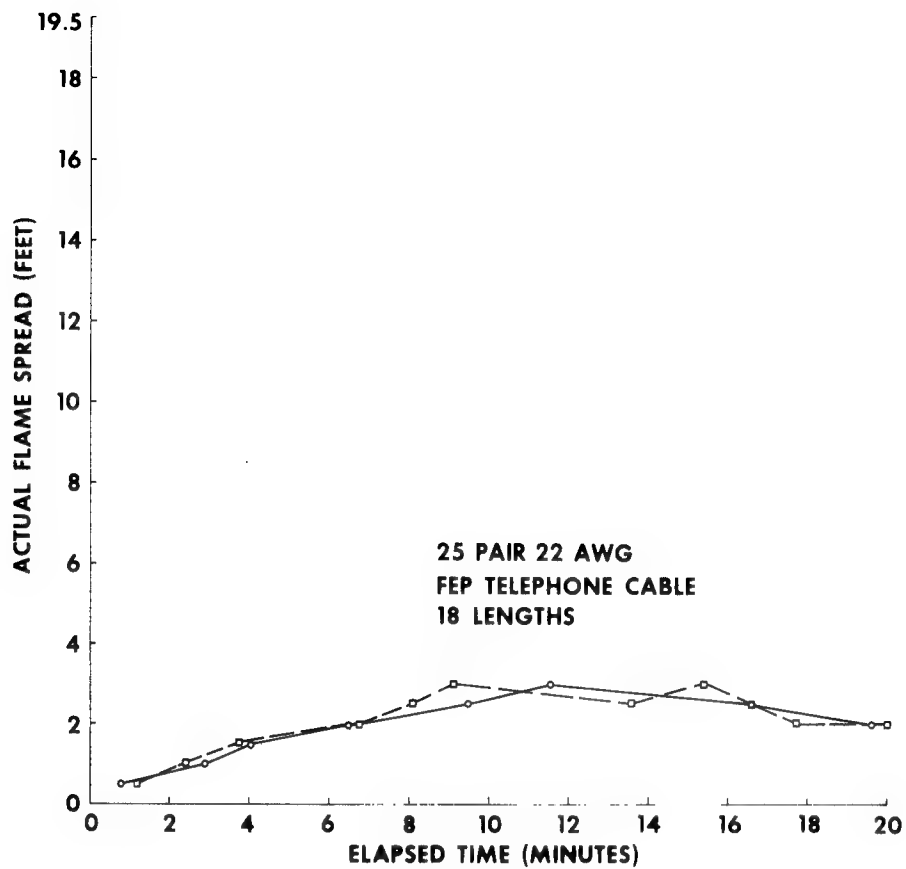


FIGURE 13

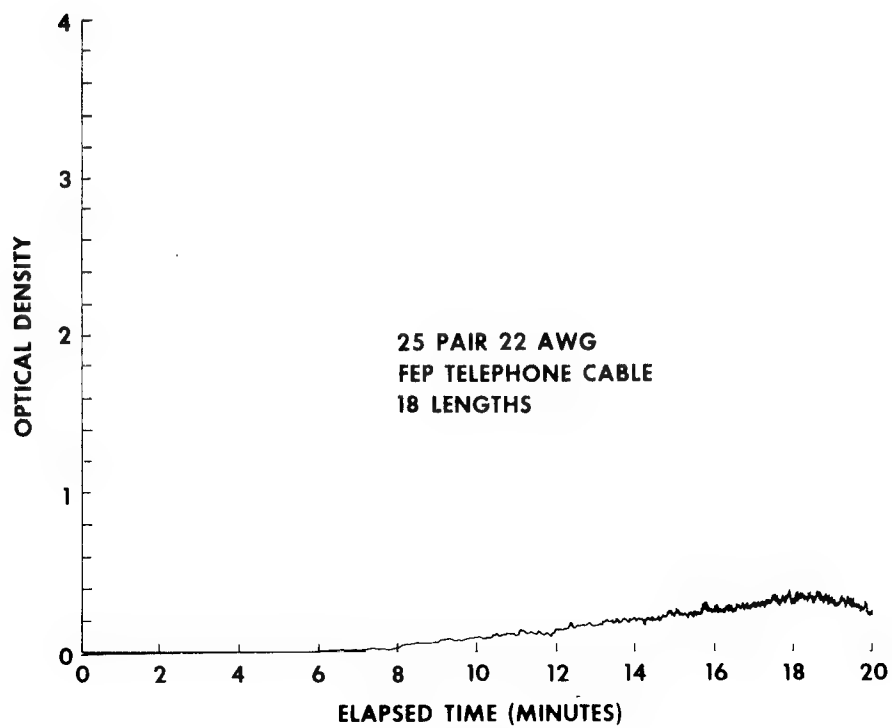


FIGURE 14

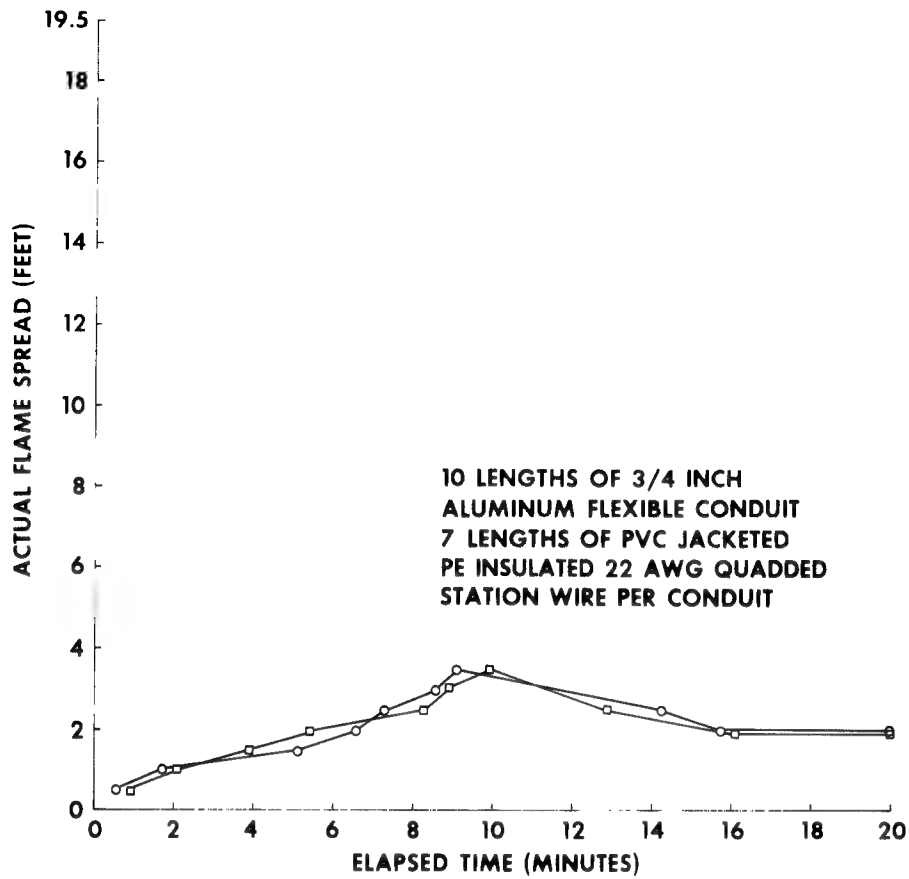


FIGURE 15

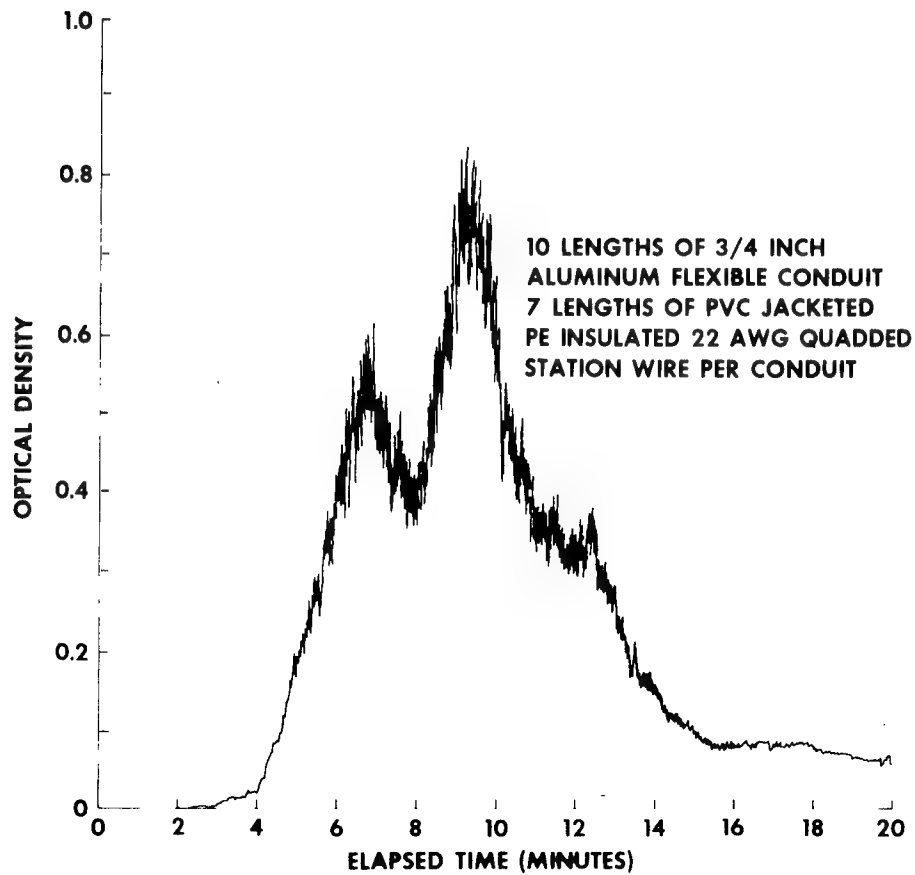


FIGURE 16

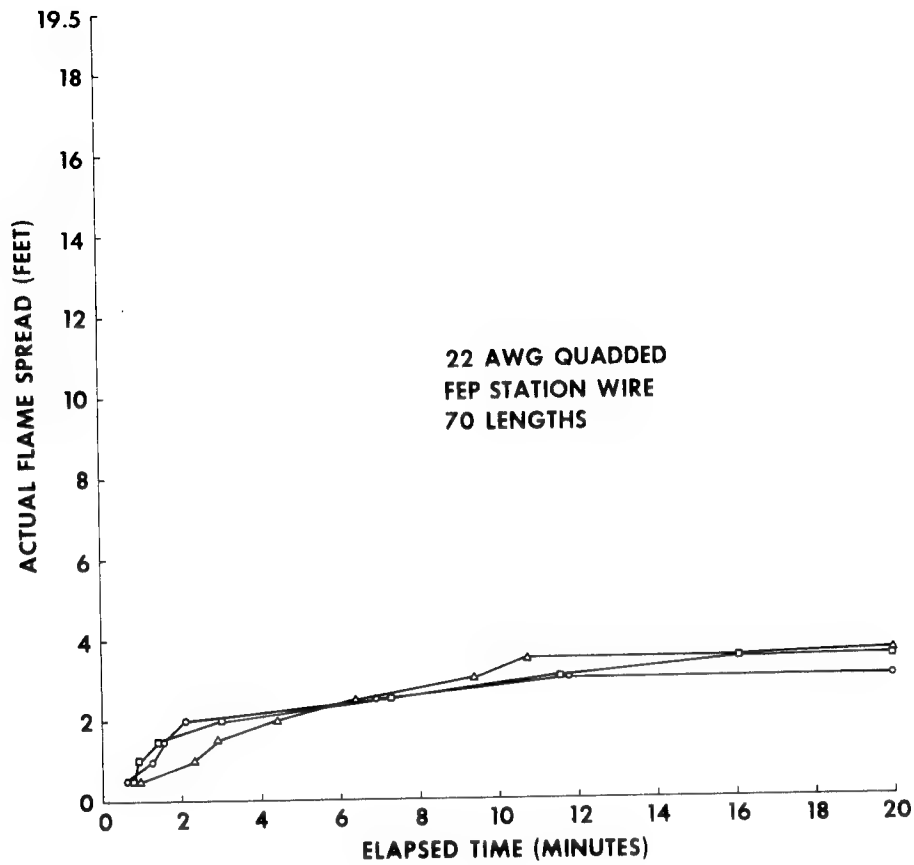


FIGURE 17

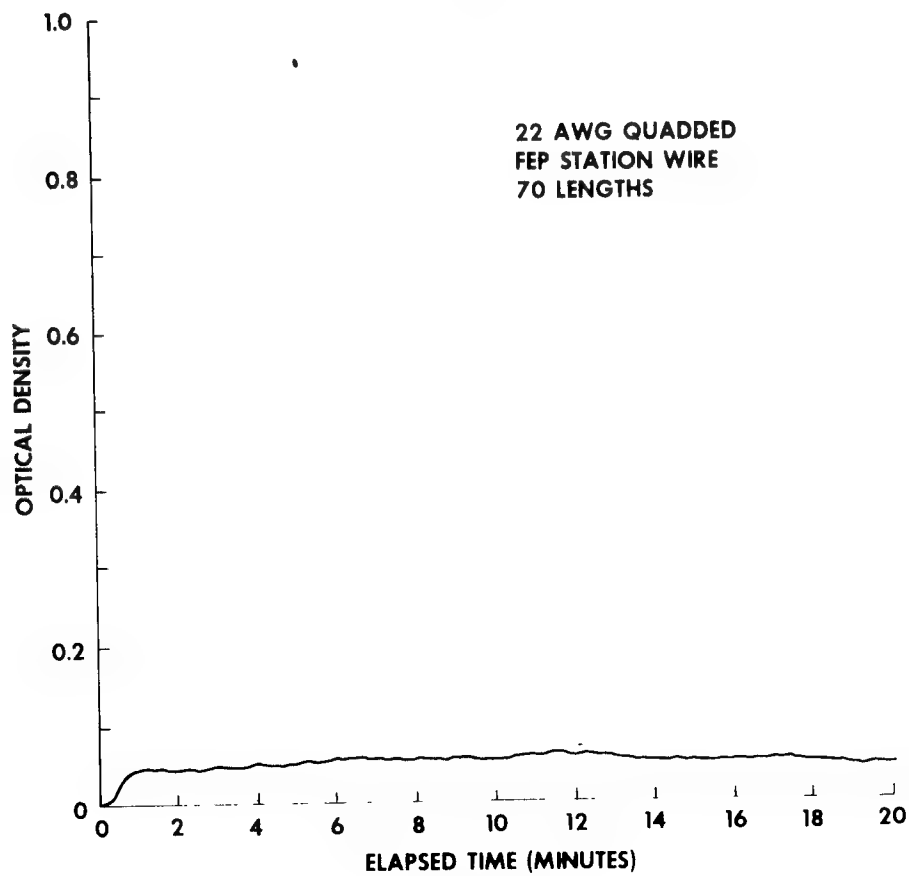


FIGURE 18

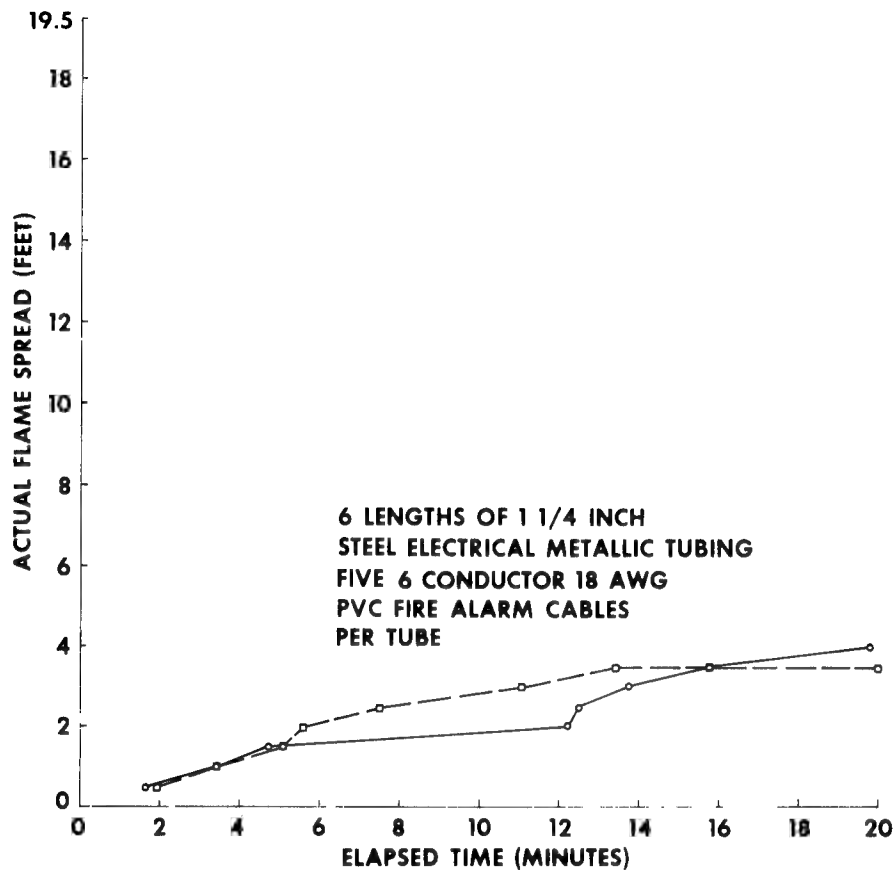


FIGURE 19

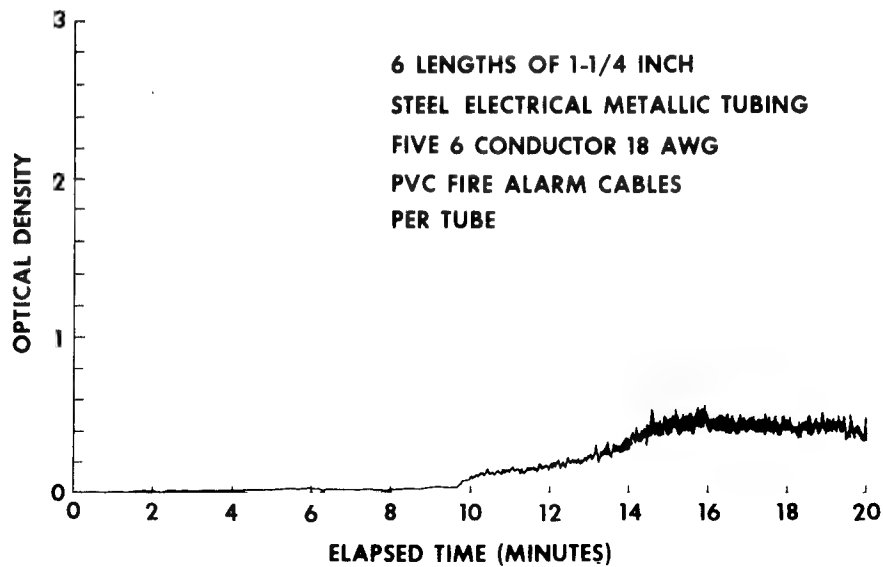


FIGURE 20

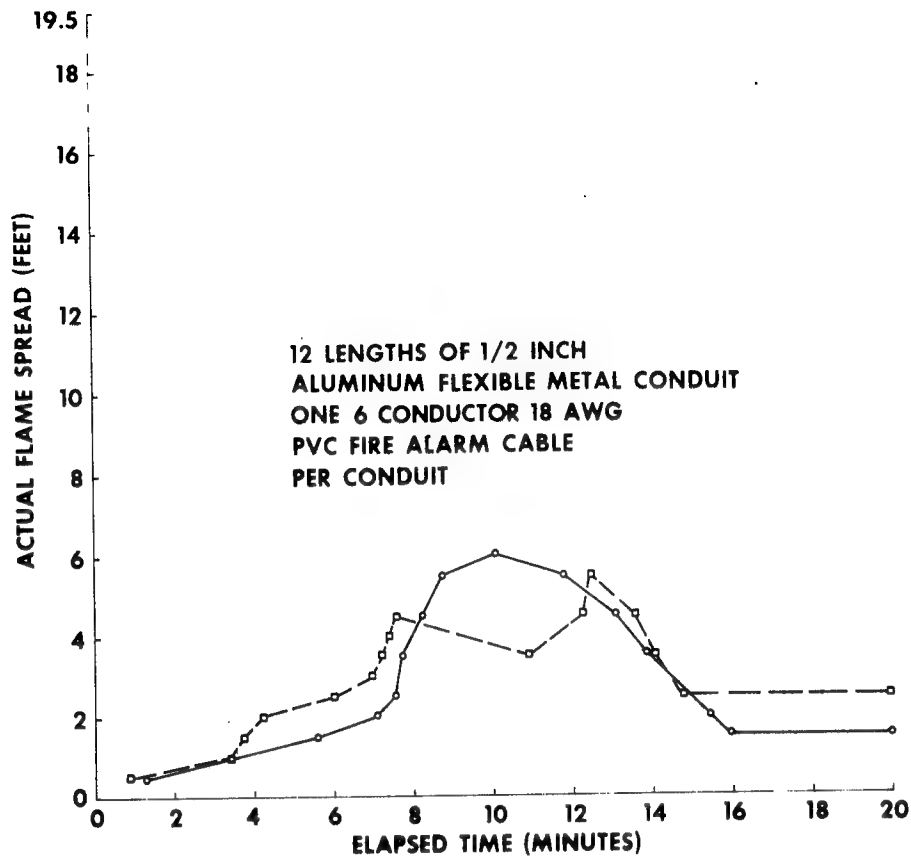


FIGURE 21

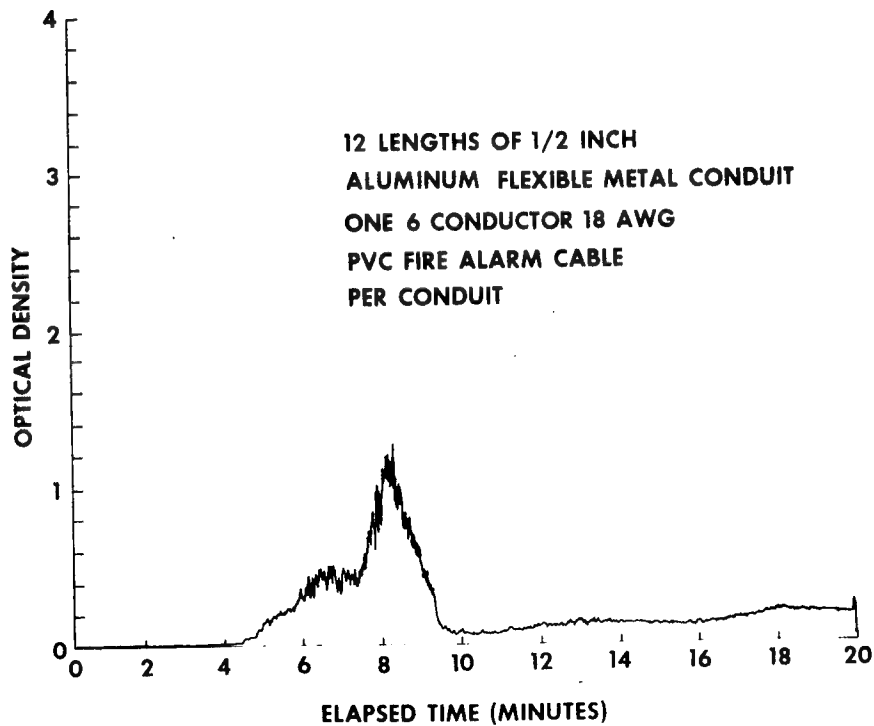
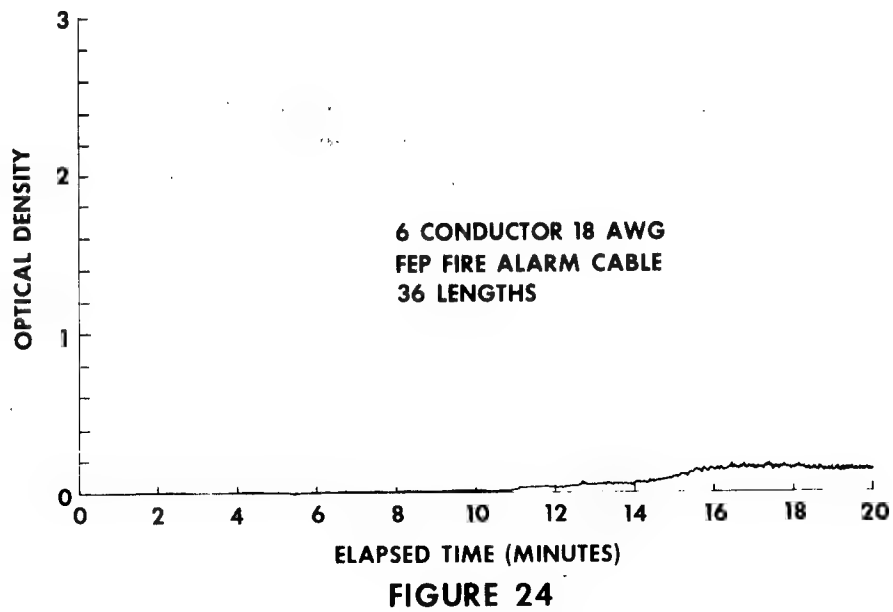
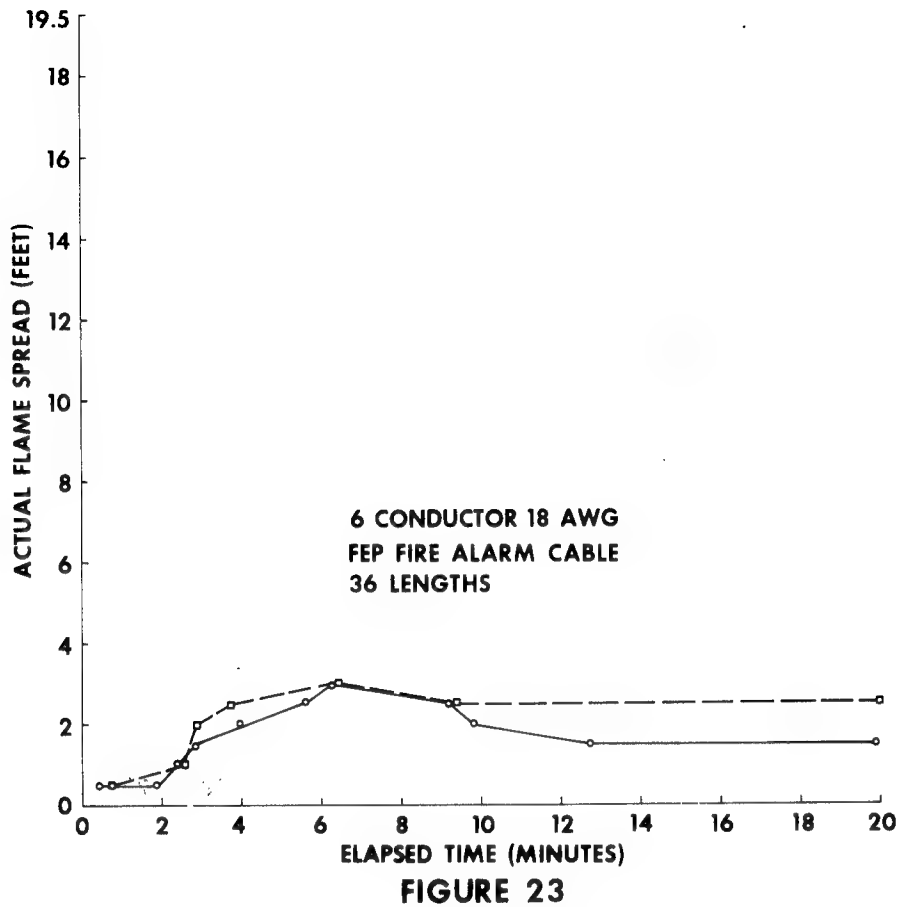


FIGURE 22



Coaxial Cable

Five lengths of 1-1/2" steel electrical metallic tubing (EMT), each containing 6 lengths of PE/PVC coax cable were tested two times. The maximum flame spreads were 7 feet and 4-1/2 feet (Figure 25). Smoke results are shown in Figure 26; average optical density for the two tests was 0.24, with a peak of 1.85 in one of the tests.

The flame spread versus time curves for 12 lengths of 1/2" aluminum flexible metal conduit, each containing one PE/PVC coax cable are shown in Figure 27. The peak flame spreads were high, 12-1/2 and 19-1/2 feet (the end of the tunnel).

The smoke curve for one test (where flame spread reached the end of the tunnel) is shown in Figure 28. Average optical density for both tests was 0.39; peak was 2.15 in one test.

Various amounts of FEP coax cable were tested. Twelve lengths produced a maximum flame spread of 3 feet (Figure 29) and very low smoke with an average optical density of 0.02 (peak 0.12 in Figure 30), far less smoke than 12 lengths of conventional cable in conduit. Twenty-one lengths produced a maximum flame spread of 3 feet and low smoke (Figure 31) with an average optical density of 0.07, and a peak at 0.25. The peak flame spread of a full rack of thirty cables was 3 feet (Figure 32) and the average optical density was 0.15, with a peak in one test of 0.60, (Figure 33) comparable smoke to 30 lengths of conventional cable in conduit.

In addition to recording flame spread and smoke results, observations were made of the conduit and cables after each test. The aluminum rigid conduit was discolored but remained virtually intact. The steel EMT was discolored with the connectors melted in the fire region (which facilitated the release of smoke). The aluminum flexible tubing was partially melted while the steel flexible tubing was only discolored. The flexible tubing with interlocked but unsealed armor permitted smoke to issue along its length. The PVC cables were a combination of ash, char and melted jacket and insulation material depending upon the severity of fire involvement. The FEP cable was melted in the fire region with the remaining sample appearing undamaged.

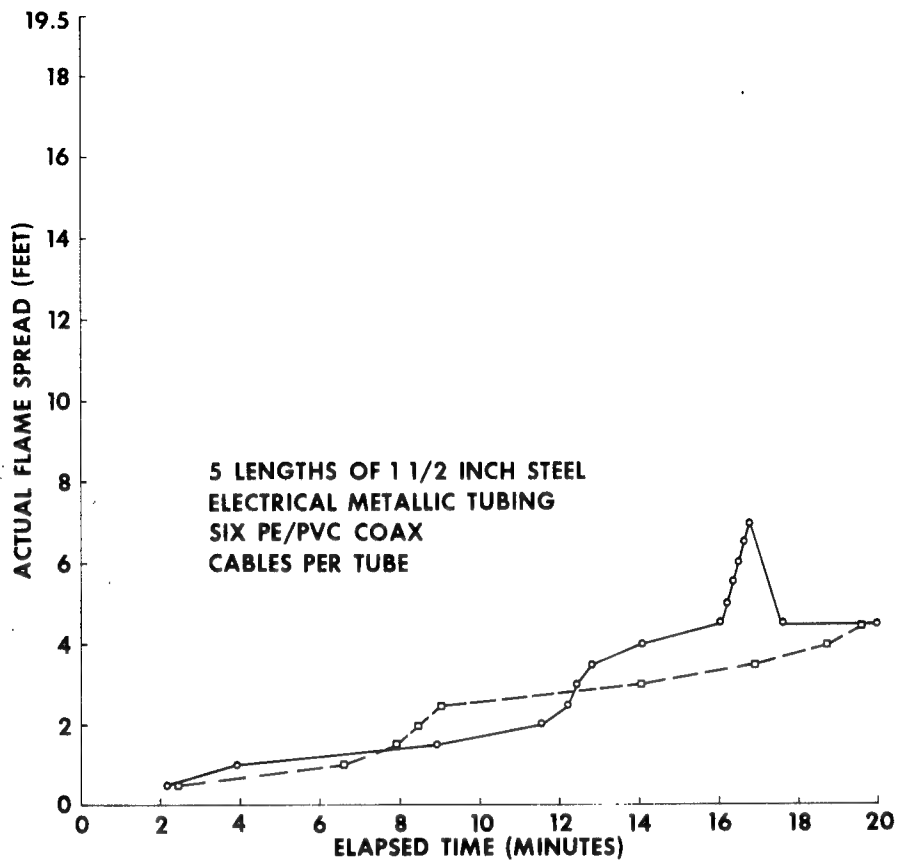


FIGURE 25

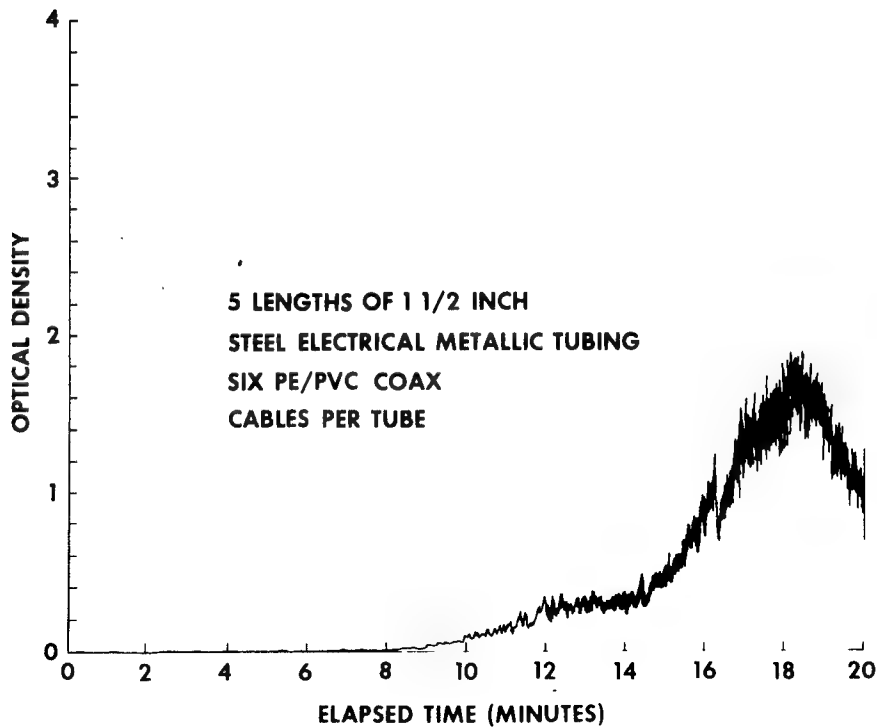


FIGURE 26

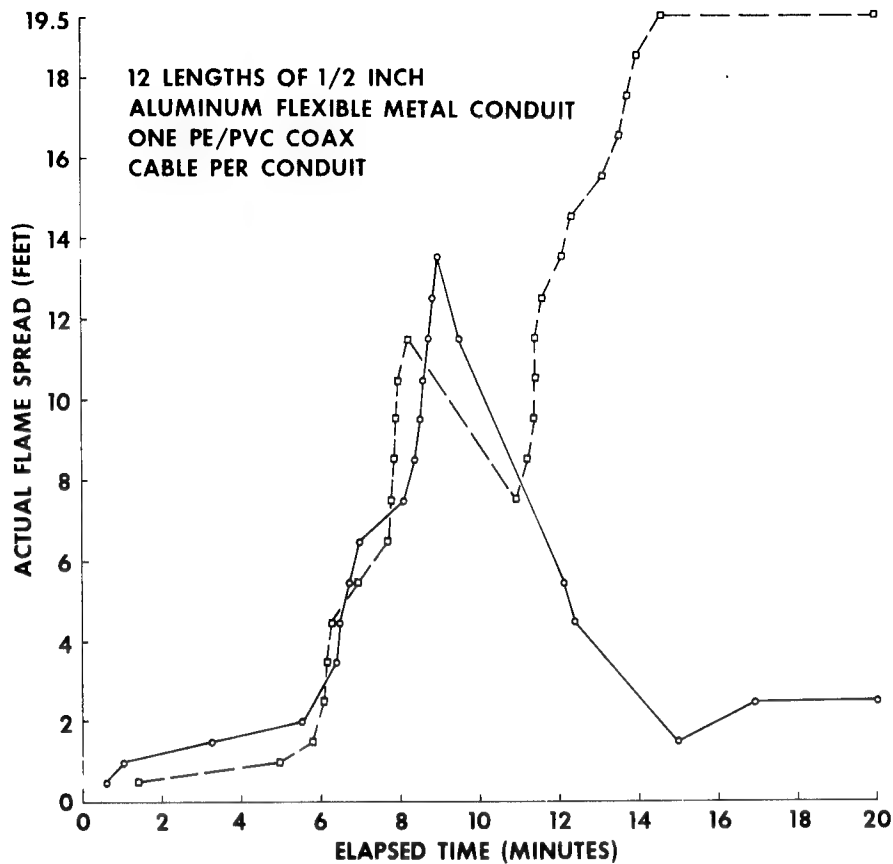


FIGURE 27

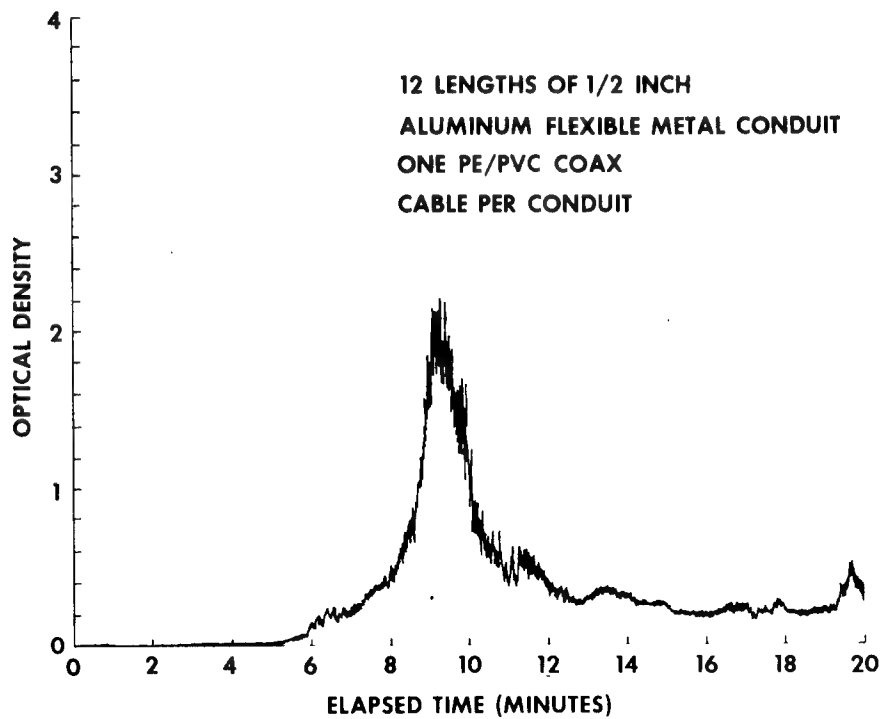


FIGURE 28

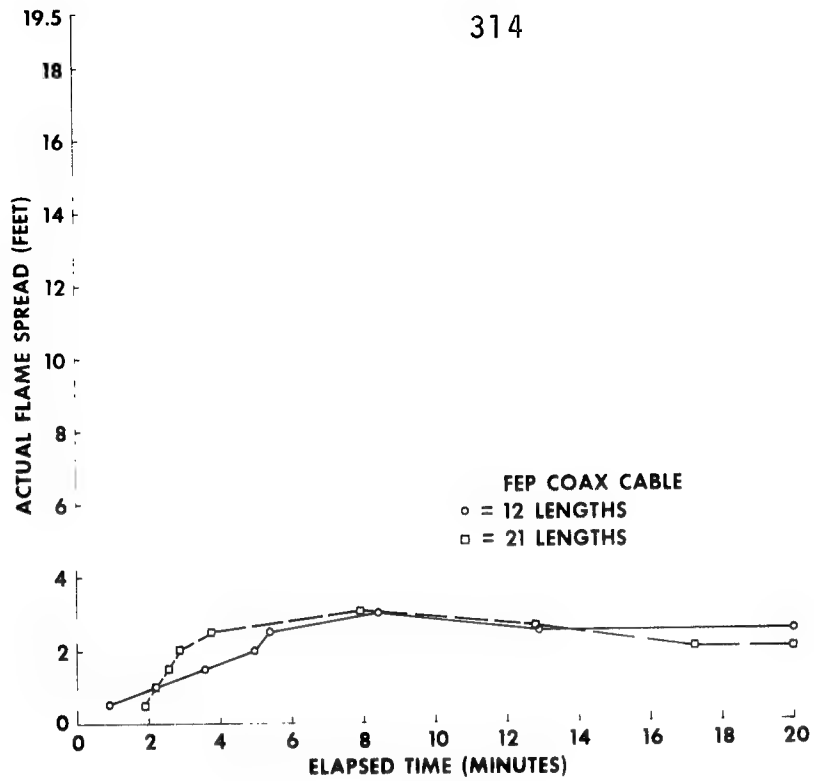


FIGURE 29

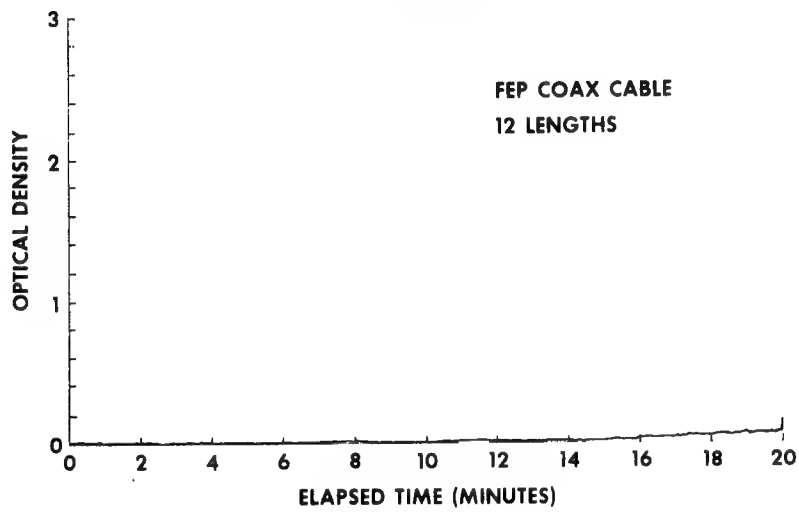


FIGURE 30

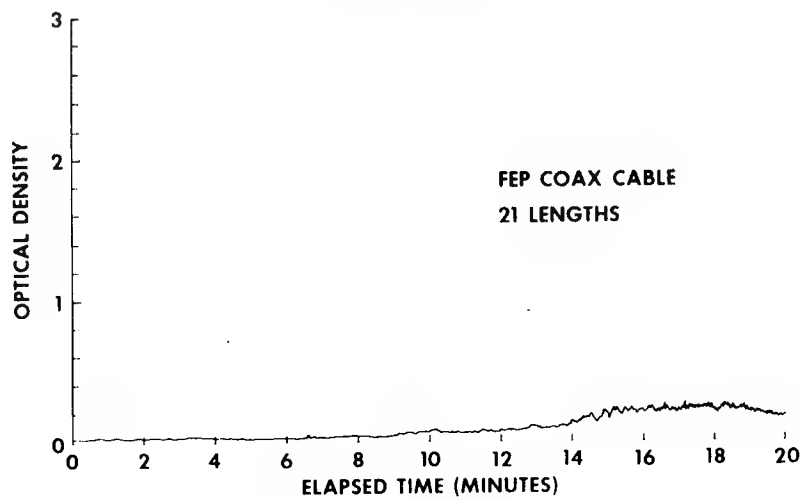
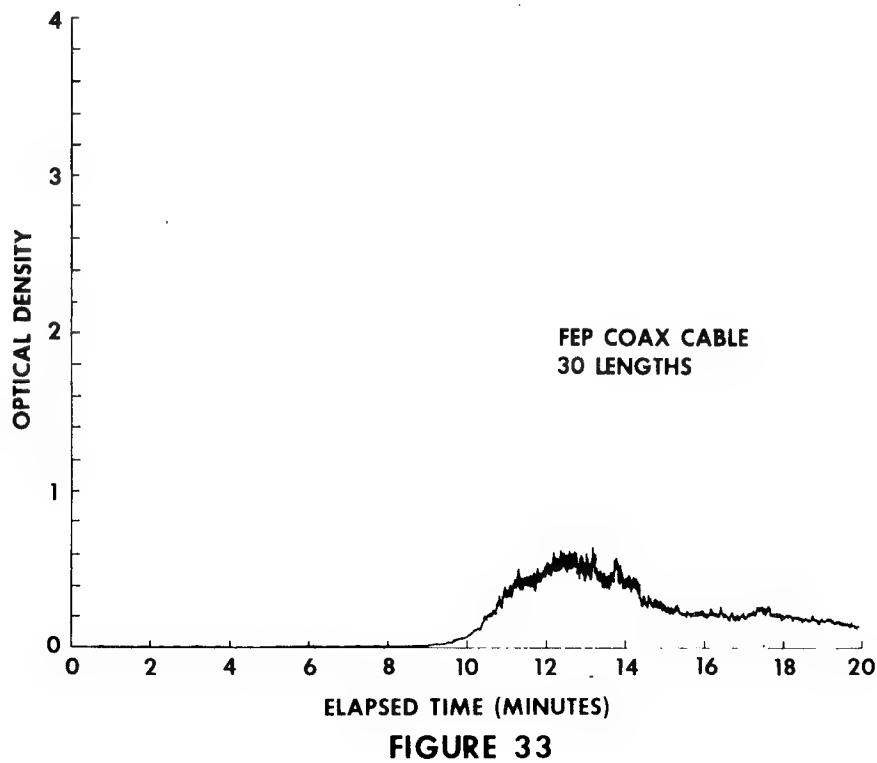
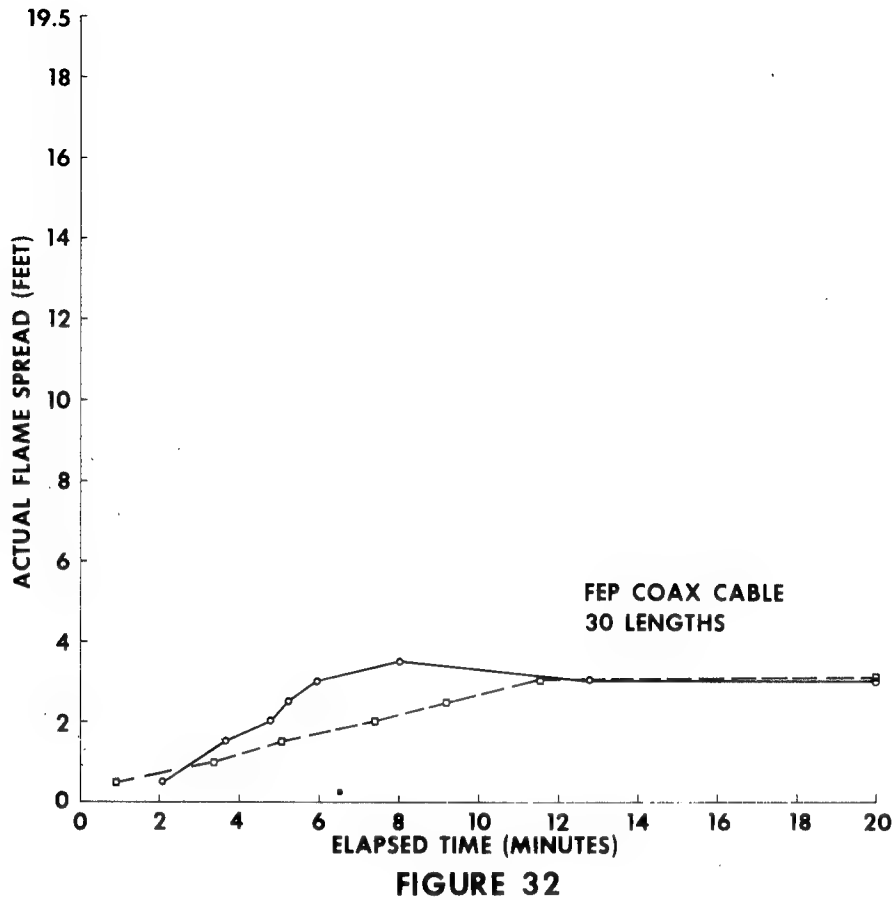


FIGURE 31



Summary and Conclusions

Four types of cable have been fire tested in the Steiner Tunnel, using the best procedures for cable: telephone inside wiring cable, telephone station wire, fire alarm cable and coaxial cable. Each type was made out of conventional materials (jacketed with PVC and insulated with either PVC or polyethylene), and tested in metal conduit, and also made out of fluorinated ethylene propylene copolymer (FEP), and tested without conduit. FEP cables not in conduit showed flame spreading and smoke generating characteristics comparable to or less than conventional cable in conduit, and have been classified by UL as to their fire resistance and smoke producing characteristics per the National Electrical Code. The flame spread and smoke data are summarized in Table II.

Acknowledgements

The authors gratefully acknowledge the contributions of J. R. Beyreis, of Underwriters Laboratories Inc., for his counsel in developing the program which lead to the Classification of these cables, and J. S. Skjordahl, of Underwriters Laboratories Inc., for conducting these fire tests.

TABLE II
Summary of Flame Spread and Smoke Results

| <u>Cable</u> | <u>Number of Cables</u> | <u>Conduit</u> | <u>Peak Flame Spread Feet</u> | <u>Peak Optical Density</u> | <u>Average Optical Density</u> |
|---------------------|---------------------------------|----------------|---|-------------------------------------|--|
| PVC Inside Wiring | 18 | aluminum | 2 | - | - |
| | 18 | rigid | 2 | .20 | .045 |
| PVC Inside Wiring | 18 | steel | 2-1/2 | .14 | .069 |
| | 18 | EMT | 2-1/2 | .38 | .094 |
| PVC Inside Wiring | 10 | steel | 2 | .06 | .008 |
| | 10 | flexible | 2 | .04 | .005 |
| PVC Inside Wiring | 10 | aluminum | 2-1/2 | .56 | .084 |
| | 10 | flexible | 2-1/2 | .31 | .051 |
| FEP Inside Wiring | 18 | - | 3 | .35 | .121 |
| | 18 | - | 3 | .25 | .047 |
| PE/PVC Station Wire | 70 | aluminum | 3-1/2 | .85 | .222 |
| | 70 | flexible | 3-1/2 | .66 | .157 |
| FEP Station Wire | 70 | - | 3-1/2 | .08 | .069 |
| | 70 | - | 3-1/2 | .07 | - |
| | 70 | - | 3-1/2 | .08 | - |
| PVC Fire Alarm | 30 | steel | 4 | .70 | .17 |
| | 30 | EMT | 3-1/2 | .50 | .09 |
| PVC Fire Alarm | 12 | aluminum | 6 | .60 | .22 |
| | 12 | flexible | 5-1/2 | 1.20 | .19 |
| FEP Fire Alarm | 36 | - | 3 | .10 | .028 |
| | 36 | - | 3 | .15 | .043 |
| PE/PVC Coax | 30 | steel | 7 | 1.85 | .37 |
| | 30 | EMT | 4-1/2 | 1.00 | .11 |
| PE/PVC Coax | 12 | aluminum | 13-1/2 | 1.85 | .45 |
| | 12 | flexible | >19-1/2 | 2.15 | .32 |
| FEP Coax | 12 | - | 3 | .12 | .015 |
| | 21 | - | 3 | .25 | .067 |
| | 30 | - | 3 | .45 | .13 |
| | 30 | - | 3 | .60 | .15 |

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8. J. R. Beyreis, J. W. Skjordahl, S. Kaufman and M. M. Yocum, "A Test Method for Measuring and Classifying the Flame Spreading and Smoke Generating Characteristics of Communication Cable," Proceedings of the Twenty-Fifth International Wire and Cable Symposium, 1976, p. 291.
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SURFACE FLAME PROPAGATION OF POLYMERS

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Abstract:

The rate of propagation of flame over the surface of a variety of polymers has been investigated under the conditions employed in the DVBR-3 test (JFF 9 156 (1978)). Some properties of the materials that materially affect the rate of flame spread are discussed. Flame retardant systems that work well under one set of burning conditions may enhance the rate of flame spread under a different set of conditions.

A primary concern of those of us working in the area of fire retardants is: How do we evaluate the effectiveness of our laboratory formulations? The tendency has been in the past to examine flammability from the quasi-steady state viewpoint. If major progress is to be made in the future in developing usable formulations, more attention must be devoted to those short lived highly dynamic periods of intense activity that occur between the steady states and largely determine the next steady state. It is for this reason that we developed a sensitive small scale test for surface "flame spreading" properties of polymers.

The flame spread test employed, i.e. DVBR-3 test, is described in detail elsewhere and will not be described here.⁽¹⁾ Basically, the test involves replacing the sample holder normally used in the Oxygen Index Test (ASTM D-2863-76) with a sample holder which holds a vertical 3/4 inch by 3 inch specimen so that a single face is exposed. The sample is placed in the OI apparatus,

the oxygen content is adjusted to the desired level and the chimney flushed for about one minute. The sample is then ignited at the top and the rate at which the flame spreads down the sample is measured.

The test is based on the premise that the rate of flame spread is a function of the "apparent" heat flux seen by the specimen just ahead of the flame front, and that an increasingly high "apparent" heat flux can be simulated by increasing the oxygen content in which the burning occurs.

Support for our premise is shown by Brauman's finding that an increase of 10 vol.% in the oxygen content of the atmosphere is approximately equivalent to superimposing an additional radiant heat flux of about 1 cal/cm^2 on a sample burning in air⁽²⁾.

Results obtained using the DVBR-3 test to evaluate the impact of various unsaturated polyester resin components upon FR-agent efficiency from a flame spread viewpoint have been reported previously^(3,4). Studies of other polymer systems have been carried out on a limited scale and are reported here.

C. E. Reineke of The Dow Chemical Company carried out a limited study of the impact of epoxy plasticizers on the flame spreading properties of PVC⁽⁵⁾. The results of this study are shown in Table 1, which shows that with epoxy plasticizers the rate of flame spread is inversely related to the flash point of the epoxy resin, i.e. the higher the measured flash point of the epoxy resin the slower the rate of flame spread. It is important to note that the OI results were independent of the flash point of the plasticizer.

An attempt was made to carry out a similar study using polyester plasticizers, but this failed since plasticizers having a significantly large spread of flash points could not be obtained. It was found that those polyester plasticizers which have known flash point gave consistently lower rates of flame spread than did the epoxy resins. Dioctyl phthalate (fl. pt. 219°C) on the other hand, gave a higher rate of flame spread than was seen with the polymeric plasticizers.

We reported previously that the results obtained from the DVBR-3 test showed considerable utility in helping us formulate glass reinforced polyester resin that would meet a desired flame spread rating in the E-84 tunnel test, and in pinpointing potential problems in the materials submitted for large scale tests⁽¹⁾.

Another class of plastics which frequently require testing under E-84 conditions are rigid polyurethane foams which are formulated for construction use. In order to determine whether or not our small scale test would have any utility in this area, a series of foams which had been evaluated in the E-84 tunnel were obtained. The composition of the foams are unknown. This information was, however, not germane to the study. The E-84 FSC's of the foams ranged from 21-49.

After a few range finding experiments it was found that the rate of flame spread was highly sensitive to the oxygen concentration of the atmosphere. As little as 1.4 vol. % change in this concentration would make the difference between conditions where the foam would not propagate the flame and those where the rate of propagation was very rapid. This was in marked contrast with the flame spreading properties of the massive polymer samples studied previously.

The results of this study are shown in Table 2. The rate at which the flame spreads under the conditions used in the DVBR-3 test generally parallel those found with the E-84 test, and appear to be useful in evaluating foams that are being designed for use in areas where the rate of flame spread is important.

The extreme sensitivity of the foams to the oxygen concentration appears to be due to the fact that the cell walls that see the heat flux from the flame are thermally thin, and very little heat is needed to raise them to their decomposition temperature. Using Brauman's equivalency factor ($10 \text{ vol. } \% \text{ O}_2 \approx 1 \text{ cal/cm}^2$) it can be estimated that as little as 0.14 cal/cm^2 external radiant heat flux will increase the rate of flame spread by a factor of ≈ 1.6 .

In attempting to use the DVBR-3 test to predict the outcome of the E-84 test, it was noted that large discrepancies would often appear. It was found that often the E-84 results would be lower than predicted. A limited study was therefore carried out to determine the affect of sample aging on the results obtained with the small scale tests.

The E-84 tests frequently were carried out several weeks after the foams were made, while the small scale tests were done within a matter of days. It was found that the flame spread rate is very sensitive to the age of the foam. In most cases it took from three days to a week before the rate of flame spread would stabilize, and in a few cases the burning rate continued to decrease even after two months. It would appear that this small scale test is very sensitive to the degree of cure of the foam and may provide a method of determining when the foam has obtained its ultimate physical, as well as flame spreading, properties.

It was also found that the rate of flame spread was not particularly sensitive to the specimen thickness, in that no notable differences were seen between 1/8 inch and 7/16 inch samples.

It was also noted that the DVBR-3 test was only useful in predicting the initial burning behavior in the E-84 tunnel, and not necessarily the final outcome of the tunnel test. The final outcome of the E-84 test apparently depends heavily on the ability of the foam to maintain its physical integrity under conditions of very high heat flux. The small scale test, not being sensitive to the ability of the foam to keep its integrity, is not useful if the foam collapses under the conditions of the E-84 tunnel test.

In the design of flame retardant materials, considerable valuable information can be obtained by burning the materials under dynamic burning conditions as well as under quasi-steady state conditions, since the outcome of the tests are controlled by different chemical and physical properties of the material.

There are no magic numbers for either dynamic (DVBR-3) or quasi-steady state (OI) tests that will indicate the outcome of large scale tests of unknown materials. Designing materials with respect to flammability consequently, becomes a matter of judgment, and the primary utility of small scale tests is to furnish bits and pieces of information upon which to base that judgment.

It must also be pointed out that the results from small scale tests may not reflect the hazard of materials under actual fire conditions.

TABLE 1
DOWNWARD VERTICAL BURNING RATES* OF EPOXY
PLASTICIZED PVC (60 wt% EPOXY) VERSUS
THE EPOXY RESIN FLASH POINT

| Flash Point °C | OI | Atmos. % O ₂ | DVBR-3 (in/min) | |
|-------------------|------|-------------------------|-----------------|------|
| | | | 50 | 100 |
| 307 | 21.4 | | 0.75 | 1.67 |
| 282 | 21.4 | | 1.05 | 2.16 |
| 182 | 22.4 | | 2.40 | 4.20 |

* Results from small scale tests may not reflect the hazard under actual fire conditions.

TABLE 2
BURNING TEST RESULTS* (Rigid Polyurethane Foams,
Compositions Unknown, ~2 lbs/ft³)

| ASTM-E84 FSC | Atmos. (% O ₂) | DVBR-3 (in/min) | | |
|-----------------|-------------------------------|-----------------|------|------|
| | | 25.2 | 26.6 | 28.0 |
| 21 | | NP | 7.2 | 11.3 |
| 23 | | NP | 9.4 | 17.1 |
| 28 | | NP | 11.3 | 17.0 |
| 39 | | 7.6 | 12.3 | 20.0 |
| 44 | | 9.2 | 14.2 | 21.9 |
| 49 | | 9.6 | 16.0 | 24.0 |

NP = No Propagation

* Results from small scale tests may not reflect the hazard under actual fire conditions.

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A NOVEL FAMILY OF FLAME RESISTANT POLYCARBONATES

Arnold Factor and Charles M. Orlando

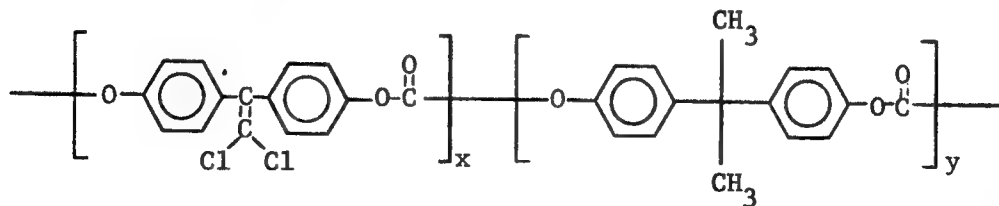
General Electric Company
Corporate Research and Development
Schenectady, New York 12301

SYNOPSIS

Although the preparation of polycarbonates based on bisphenol A and 2,2-bis(4-hydroxyphenyl)-1,1-dichloroethylene was disclosed in 1964 by Porejko et al (1), little has been reported on their physical and flammability properties. In order to define the properties of this system these materials were prepared and evaluated. The results indicate that both the copolymers and the blends of the homopolycarbonates of the two different bisphenols result in transparent thermoplastics possessing nearly the same attractive physical properties as the homopolycarbonate from bisphenol A. In addition, many of these formulations possess flame resistant properties exceeding those of other transparent thermoplastics, e.g. highest OI, lowest smoke and lowest ratings in the ASTM E84 tunnel and E162 radiant panel tests. In addition, preliminary bioassay results with rats of the products from 500°C air pyrolysis gives an LD₅₀ value greater than that of other common thermoplastics.

INTRODUCTION

The preparation of polycarbonates based on 1,1-dichloro-2,2-bis(4-hydroxyphenyl) ethylene (BPC) was first reported in 1964 as a copolymer with bisphenol A (BPA) by Porejko et al (1), as shown below,



and later in 1968 as the homopolymer (2). In these and subsequent reports by these same workers (3-5), only a brief description was given of the physical and flammability properties of these polymers. In order to better

define the properties of this system, these materials were prepared and evaluated. The results of this work is the subject of this paper.

SYNTHESIS

The synthetic route to BPC and its subsequent polymerization is outlined in Scheme I. The condensation step, Eq. 1, is most conveniently carried out in a sulfuric acid/acetic acid mixture giving purified yields of up to 70% (2). Other acid systems such as anhydrous HCl (2,6), sulfuric acid/water (7a), sulfuric acid/methylene chloride (7b), acid ion exchange resin (8) and anhydrous HF (9) also are effective. The dehydrohalogenation step, Eq. 2, was most conveniently effected using methanolic KOH (2,10); however, other efficient base systems are liquid ammonia (11), LiCl in dimethylformamide (DMF) (12), and MOH (13) or M_2CO_3 (13) [M = Na or K] in DMF.

Early in this work it was discovered that the properties, especially color and impact, of the polymers made from BPC depended on the purity of this monomer (12). Thus special care was taken to purify BPC by multiple recrystallizations, e.g. from MeOH/H₂O, until the required purity (12) was attained in ~70% yield.

Polymerization was performed using the standard interfacial technique (14) in methylene chloride. Copolymer systems containing various combinations of BPC and BPA were run without any change in procedure. Generally, 2.5 mole % of phenol was employed as a chain stopper yielding material whose intrinsic viscosity, $[\eta]^{25^\circ}_{CHCl_3}$, ranged from 0.50 to 0.55 dl/g. Polymers made in this way were isolated by steam precipitation (23).

In order to make test parts, the above material was dried at 250°F for at least 3 hours in an air circulating oven, extruded into pellets at 510°-550°F and injection molded using a melt temperature of 570°F and mold temperature of 200-205°F. Compression moldings, when required, were performed at ~500°F.

PROPERTIES

Homopolymer and Copolymer Properties

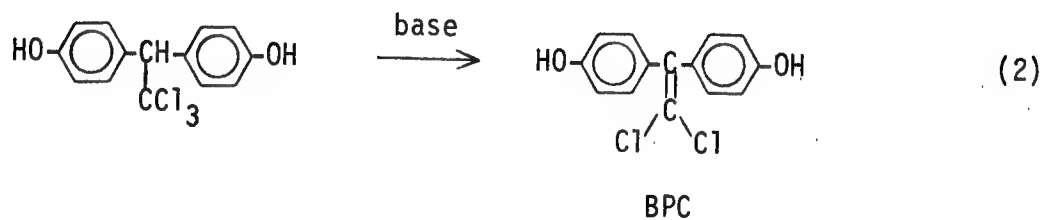
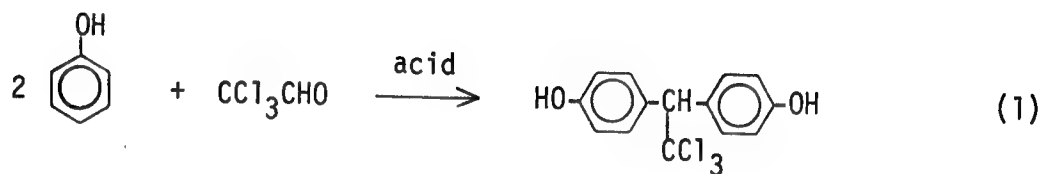
The physical, thermal and mechanical properties of the homopolycarbonate of BPC (BPC-PC) are tabulated in Table I. This data indicates that this polymer possesses nearly the same attractive property profile as BPA polycarbonate (BPA-PC). Similarly the physical properties of copolycarbonates of BPC and BPA, shown in Table II, are virtually constant across the whole compositional range.

Properties of BPC-PC/BPA-PC Blends

In the course of this work it was found that BPC-PC was optically compatible in blends with a number of polyesters and polysulfones over a wide concentration range. Of particular interest it was found that blends of BPC-PC and BPA-PC were optically compatible at all compositions and, as shown in Table III, show virtually constant mechanical properties over the total range.

Scheme I
Overall Synthetic Route

Monomer Synthesis



Polymerization

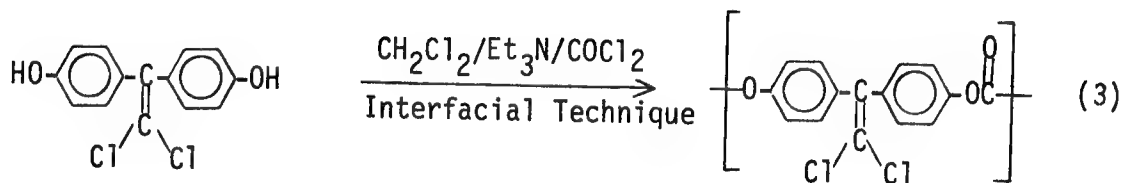


Table I

Properties of BPC Homopolymer

| Property | ASTM Method | Test Value |
|---|-------------------------------------|-------------------------------------|
| <u>Physical</u> | | |
| Specific Gravity | -- | 1.40 g/cc |
| Refractive Index (25°C) | -- | 1.61 |
| % Water Retention (25°C) | -- | 0.26 |
| Water Vapor Transmission Rate (g/100 in ² /24 hrs-100°F/90% r.h.) | -- | 7.5 |
| Gas Permeability (10 ⁹ cc gas (25°) x cm/sec/cm ² /cm Hg | -- | |
| O ₂ | | 0.097 |
| N ₂ | | 0.02 |
| H ₂ O | | 23.8 |
| Freon 22 and 13 | | 0.006 |
| <u>Thermal</u> | | |
| Heat Deflection Temp. (at 264 psi) | D 648 | 290°F/144°C |
| Glass Transition Temp. | -- | 168°C |
| <u>Mechanical</u> | | |
| Tensile Strength | D 638 | |
| Yield | | 11,100 psi |
| Ultimate | | 11,500 psi |
| Elongation, Rupture | D 638 | 70-113% |
| Flexural Strength | D 790 | 16,200 psi |
| Flexural Modulus | D 790 | 3.76 x 10 ⁵ psi |
| Notched Izod Impact | D 256 | 14-16 ft-lbs/in ^a |
| Gardner Impact | -- | >320 in-lbs |
| Melt Flow (g/10 mins) | D 1238 (Procedure A, Cond. 0) | 0.9-0.8 1.8 (85/15) ^b |
| Taber Abrasion Resistance (% Haze/100 cycles) | -- | 29.2 (90/10) ^b |

^aMaterial with ductile behavior (impacts of 14-16 ft lb/in) is only achieved when monomer of sufficient purity is utilized (12).

^bAlthough these values are primarily for the homopolymer, values for the BPC/BPA system are noted when significantly different or when homopolymer value is not available.

Table II
Properties of BPC/BPA Copolycarbonates

| BPC/BPA | 100/0 | 85/15 | 50/50 | 25/75 | 10/90 | 5/95 |
|--|--------|--------|-------|-------------------|--------|-------------------|
| Notched Izod Impact (ft-lbs/in) | 16 | 16 | 17 | 2/17 ^a | 18 | 3/19 ^a |
| Heat Deflection Temp. (°C) | 143° | 141° | 127° | 120° | 130° | 121° |
| Tensile Strength, psi | | | | | | |
| Yield | 10,200 | 10,100 | 9,559 | 9,265 | 9,067 | 9,200 |
| Ultimate | 13,500 | 11,300 | 8,625 | 10,364 | 11,644 | 9,971 |
| Elongation, % | | | | | | |
| Yield | 11.0 | 11.0 | 11.4 | 10.7 | 10.7 | 10.2 |
| Rupture | 67 | 61 | 37 | 87 | 115 | 95 |
| Flex. Strength ($\times 10^{-4}$ psi) | 1.6 | 1.6 | 1.6 | 1.6 | 1.5 | 1.5 |
| Flex. Modulus ($\times 10^{-5}$ psi) | 3.6 | 3.6 | 3.6 | 3.5 | 3.5 | 3.4 |

^aBimodal behavior

Table III

Properties of BPC-PC/BPA-PC Blends

| BPC-PC/BPA-PC | 100/0 | 90/10 | 75/25 | 50/50 | 25/75 | 10/90 | 0/100 |
|--|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Notched Izod Impact (ft-lbs/in) | 16 | 17 | 17 | 17 | 17 | 18 | 18 |
| Gardner Impact (in-lbs) | >320 | >320 | >320 | >320 | >320 | >320 | >320 |
| Heat Deflection Temp. (°C/°F) | 142°/288° | 140°/284° | 140°/284° | 133°/271° | 131°/268° | 128°/262° | 127°/261° |
| Glass Transition-Tg(°C) | 169° | 165° | 164° | 160° | 154° | 152° | 152° |
| Tensile Strength, psi | | | | | | | |
| Yield | 10,040 | 9760 | 9430 | 9000 | 8580 | 8480 | 8470 |
| Ultimate | 9450 | 9580 | 9140 | 10,310 | 9490 | 9970 | 10,140 |
| Elongation, % | | | | | | | |
| Yield | 11.1 | 11.1 | 10.9 | 10.4 | 10.3 | 10.1 | 9.5 |
| Rupture | 38 | 49 | 50 | 87 | 89 | 105 | 110 |
| Flex. Strength ($\times 10^{-4}$ psi) | 1.63 | 1.64 | 1.58 | 1.54 | 1.50 | 1.47 | 1.48 |
| Flex. Modulus ($\times 10^{-5}$ psi) | 3.66 | 3.58 | 3.56 | 3.42 | 3.29 | 3.31 | 3.34 |
| Molded $[\eta]_{\text{CHCl}_3}^{25^\circ}$ (dl/g) ^a | 0.48 | 0.48 | 0.50 | 0.54 | 0.54 | 0.57 | 0.56 |

^aPowder $[\eta]$'s: BPC-PC, 0.56; BPA-PC, 0.57

The Effect of Molecular Weight on Notched Izod Impact

It is well known that the mechanical properties of a polymer greatly depend on its molecular weight, e.g., in the case of BPA-PC, an $[\eta]$ of greater than 0.45 dl/g (15) is required before the desirable properties usually associated with this material are developed. Studies on the effect of molecular weight on the notched izod impact of BPC based polycarbonates, shown in Figure 1, indicate that a change from brittle behavior, e.g., impact values of ~ 2 ft-lb/in, to ductile behavior, eg., impact values of ~ 16 ft-lb/in, occur over the $[\eta]$ range of 0.39-.46 dl/g $[\eta]$ for BPC homopolycarbonate and 0.38 and 0.44 dl/g, for the 85/15 BPC/BPA copolymer. From the relationship between $[\eta]$ and M_n (vide infra), it is apparent that a M_n of greater than 17,000 g/mol is necessary to achieve high impact behavior.

Electrical Properties

The electrical properties of a 90/10 BPC-PC/BPA-PC blend, shown in Table IV, indicate that this material is well suited for use in most electrical and electronic applications.

Table IV

Electrical Properties of 90/10 BPC-PC/BPA-PC Blend

| Property | ASTM Method | Test Value |
|--|-------------|-----------------------|
| Dielectric Strength (S/S in oil) | D 149 | 530 volts/mil |
| Dielectric Constant | D 150 | |
| 60c | | 3.18 |
| 1 kc | | 3.16 |
| 1 mc | | 3.01 |
| Power Factor (%) | D 150 | |
| 60 c | | 0.16 |
| 1 kc | | 0.14 |
| 1 mc | | 0.74 ¹⁶ |
| Volume Resistivity (ohm-cm) | D 150 | 2.79×10^{16} |
| Arc Resistance, sec. (Stainless Steel Electrodes) | D 495 | 3.71 |

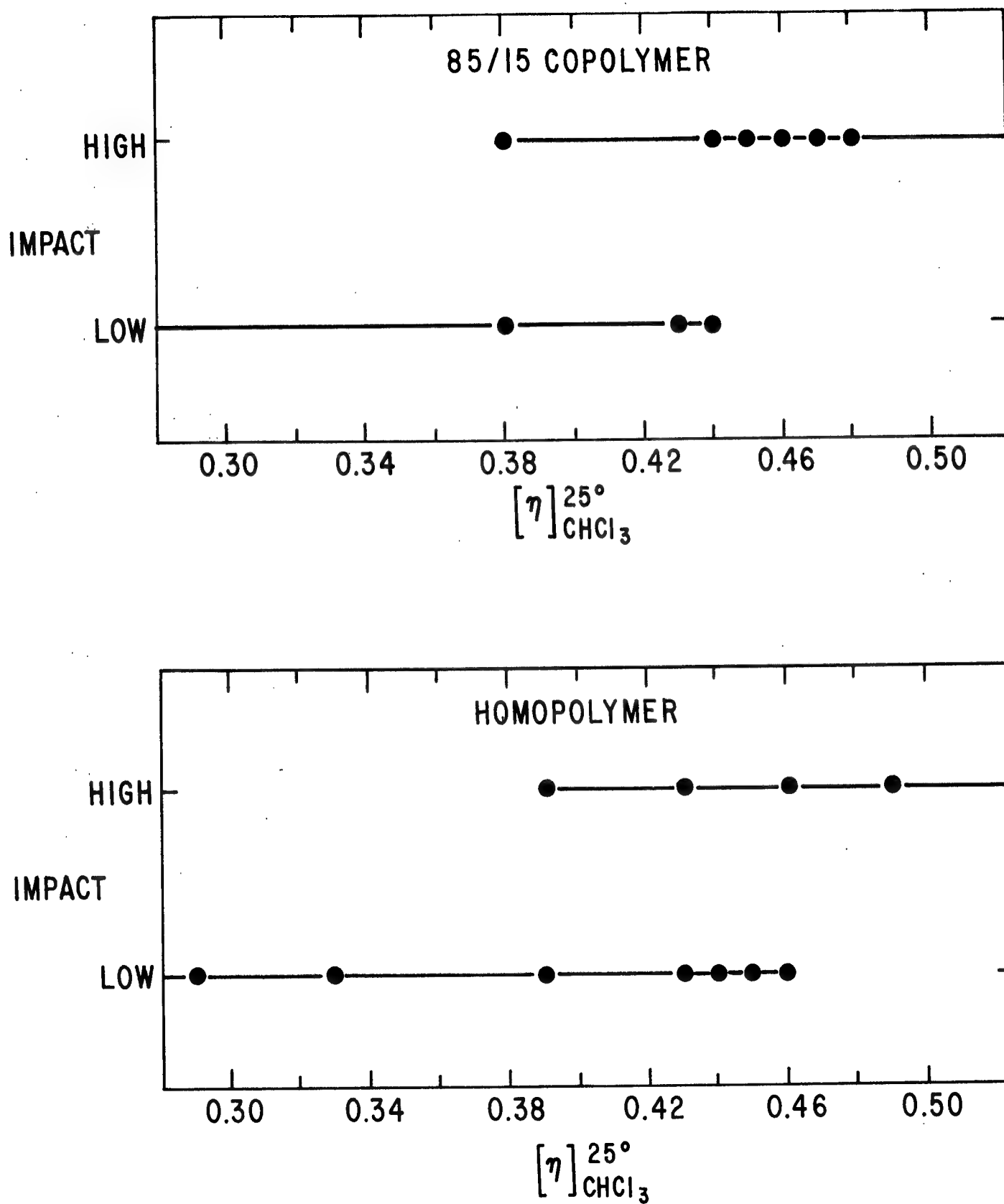


Figure 1. The Effect of Molecular Weight on Notched Izod Impact.

Solubility Properties

The solubility properties of a 90/10 BPC-PC/BPA-PC blend was assessed in a variety of solvents by attempting to make a 1% solution of the polymer at room temperature under constant stirring and noting the time required to dissolve. In those cases where complete dissolution failed to occur, the solutions were heated and the temperature where the polymer finally dissolved noted. These results, shown in Table V, indicate that the polymer was generally soluble in halocarbon and aromatic liquids.

Effect of Solvent on Intrinsic Viscosity

The effect of solvent on the value of $[\eta]$ for a 85/15 BPC/BPA copolymer is shown in Table VI.

Table VI
Effect of Solvent^a on the Intrinsic
Viscosity of 85/15 BPC/BPA Copolymer

| <u>Sample</u> | <u>Mn^b x 10⁻³</u> | <u>$[\eta]_{\text{CH}_2\text{Cl}_2}^{25^\circ}$</u> | <u>$[\eta]_{\text{CHCl}_3}^{25^\circ}$</u> | <u>$[\eta]_{\text{THF}}^{25^\circ}$</u> |
|---------------|---|--|---|--|
| 1 | 16.2 | 0.38 dl/g | 0.39 dl/g | 0.43 dl/g |
| 2 | 19.0 | 0.54 | 0.57 | 0.57 |
| 3 | 23.2 | 0.61 | 0.65 | 0.67 |

^aSolubility parameters: CH_2Cl_2 , 9.7; CHCl_3 , 9.3; THF, 9.1

^bNumber average molecular weight determined by osmometry in toluene.

This data suggests that the solubility parameter of this polymer is probably less than 9.1, although the possibility exists that some molecular weight degradation may have occurred in the more acidic halocarbon solvents. Based on this preliminary data, one can derive a Staudinger-Kuhn equation, $[\eta] = KM^a$, e.g.,

$$[\eta]_{\text{THF}}^{25^\circ} = 3.34 \times 10^{-6} \cdot M_n^{1.22} \quad (4)$$

Table V

Solubility of 90/10 BPC-PC/BPA-PC

| Solvents | Solubility ($\geq 1.0\%$) at 27° | | Solubility ($\geq 1.0\%$) at Elevated Temp. | |
|---------------------------|------------------------------------|-----------------|---|---------------|
| | Solubility | Time Req. (min) | Solution Temp. | Precip. Temp. |
| Methylene chloride | soluble | <5 | $\leq 27^\circ\text{C}$ | - |
| Chloroform | " | <5 | " | - |
| Tetrahydrofuran | " | 5 | " | - |
| Thiophene | " | 5 | " | - |
| Dibromomethane | " | 5 | " | - |
| Pyridine | " | 10 | " | - |
| Dioxane | " | 10 | " | - |
| 1,1,2-Trichloroethane | " | 10 | " | - |
| Chlorobenzene | " | 10 | " | - |
| sym-Tetrachloroethane | " | 14 | " | - |
| Bromobenzene | " | 15 | " | - |
| Epichlorohydrin | " | 17 | " | - |
| Bromoform | " | 20 | " | - |
| Benzonitrile | " | 20 | " | - |
| Nitrobenzene | " | 25 | " | - |
| Phenylacetone | " | 25 | " | - |
| Methylbenzoate | " | 30 | " | - |
| Toluene | " | 34 | " | - |
| Phenetole | " | 60 | " | - |
| Benzyl acetate | " | 60 | " | - |
| Ethyl benzene | " | 72 | " | - |
| Isopropyl benzene | " | 110 | " | - |
| Tetralin | " | 110 | " | - |
| Ethylene glycol diacetate | " | 116 | " | - |
| Diphenyl ether | " | 120 | " | - |
| 1-Chloronaphthalene | " | 180 | " | - |
| sym-Tetrabromoethane | " | 180 | " | - |
| Acetone | Insoluble | - | | |
| Dimethylsulfoxide | " | - | 140°C | 65°C |
| Hexamethylphosphoramide | " | - | 67°C | - |
| Diethyl phthalate | " | - | 56°C | - |
| Methanol | " | - | Insoluble ($\leq 1.0\%$) | |
| Ethanol | " | - | " | " |
| Carbon tetrachloride | " | - | " | " |
| Acetonitrile | " | - | " | " |

FLAMMABILITY TESTING

Key Flammability Properties

Studies have shown that optimum flame resistant properties are developed in BPC/BPA systems containing greater than 85% BPC. In addition, in this range it was found that within experimental error the flammability properties depended only on the BPC content and not on whether one had a copolymer or a blend. Key flammability properties of these materials are shown in Table VII. Comparison of these results with those from several typical commodity resins, shown in Table VIII, indicate that the formulations containing 85% BPC or greater are much more flame resistant than other thermoplastics.

Oxygen Index Studies

An anomalous effect was found in the oxygen indexes (OI) of these systems at higher concentrations of BPA. As shown in Figure 2, the OI values of samples of blends prepared by compression molding and samples of copolymers, prepared either by injection or compression molding, all showed a straight line relationship. In contrast, the OI's of a blend series, prepared by pellet extrusion followed by injection molding, showed a plateau effect of OI values of greater than 50 for compositions containing 25 to 100% BPC-PC. The reason for this effect and its significance in larger fire tests are presently unknown.

Fire Resistance of Structural Foams

The fire resistance of a series of structural foams prepared from blends of BPC-PC and BPA-PC using a chemical blowing agent (16) was assessed using oxygen index, the NBS smoke chamber, and the ASTM E162 radiant panel test. This latter test was performed in two different test laboratories, and while there was some disagreement in results at higher BPA-BPC concentrations, the I_s values reported in Table IX along with high OI values all indicate the outstanding flame resistance of these materials. In addition, the low D_m (corr.) values found for materials containing 80% or greater BPC-PC indicate that the low smoke characteristics of the solid polymer is also exhibited by the analogous foamed compositions.

TOXICOLOGICAL CONSIDERATIONS

When considering the utility of a new flame resistant polymer, one must consider the potential hazards involved in both its manufacture and its end use. Towards this end, studies have been made to evaluate the potential toxicity of the monomer and its intermediate, the biodegradability of the monomer, and the toxicity of the gases produced when the polymer is burned.

Table VII

Flammability Properties of BPC/BPA Polycarbonates

| Property ^a | Test Method | BPC/BPA Composition | | | |
|--|--------------|---------------------|-------|-------|--|
| | | 100/0 | 90/10 | 85/15 | |
| Oxygen Index | D2863 | 56 | - | 50 | |
| UL Subject 94 | --- | 5V | 5V | 5V | |
| Radiant Panel (Is) - (1/8") | E162 | 0 | - | 11 | |
| Smoke | | | | | |
| - NBS Chamber (DM corr.) | NFPA No. 258 | | | | |
| Flaming (1/8") | | 67 | 19 | 31 | |
| Non Flaming (1/8") | | 1 | - | 10 | |
| - XP-2 Chamber (Smoke Density Rating) | D2843 | - | - | 4.5 | |
| - Arapahoe Chamber ^b (% Smoke) | --- | 0.8% | - | 1.7% | |
| 25' Tunnel Test | E84 | | | | |
| Flame Spread Rating (1/8") | | - | - | 20 | |
| Smoke Rating (1/8") | | - | - | 200 | |
| Fuel Contribution Value (1/8") | | - | - | 0 | |

^aThe flame tests described are not intended to reflect hazards presented by these or any other materials under actual fire conditions.

^bBased on weight lost (amount burned).

Table VIII
Flammability Properties of Commodity Resins[†]

| Property | Test Method | Polystyrene | Polypropylene | Polymethyl Methacrylate | PVC |
|--|--------------|-------------|---------------|--------------------------|----------------|
| Oxygen Index ^a | D2863 | 18.0 | 17.4 | 17.3 | 45 |
| UL94 | -- | HB | HB | HB | V-0 |
| Radiant Panel ^b (I _s) | E162 | 355(.066") | - | >376(.125") ^e | 3.2-9.6(.147") |
| Smoke | | | | | |
| - NBS Chamber ^a (DM Corr.) | NFPA No. 258 | | | | |
| Flaming (1/4") | | 780 | 119 | 90 | 535 |
| Non Flaming (1/4") | | 395 | 780 | 195 | 470 |
| - XP-2 Chamber ^c (Smoke Density Rating) | D2843 | 98 | 20 | 2 | 100 |
| - Arapahoe Chamber ^d (% Smoke) | | 12.7 | - | 0.19 | 10.5 |
| 25' Tunnel Test | E84 | | | | |
| Flame Spread Rating | | - | - | ~240 (1/4") | - |
| Smoke Rating | | - | - | ~450 (1/4") | - |

^aC.J. Hilado, "Flammability Handbook for Plastics", Technomic Press, Westport, CT, 2nd Edition (1974).

^bIbid, 1st Edition (1969)

^cNTIS, "Physio-Chemical Study of Smoke Emission by Aircraft Interior Materials, Part I" by National Aviation Facilities Experimental Center for FAA (1973).

^dC.J. Hilado and A.M. Machado, J. Fire and Flammability, 9, 240 (1978), % Smoke Based on weight loss (amount burned).

^eValue of 376 was given for FR acrylic, it seems reasonable that non FR will give a higher value.

[†] The flame tests described are not intended to reflect hazards presented by these or any other materials under actual fire conditions.

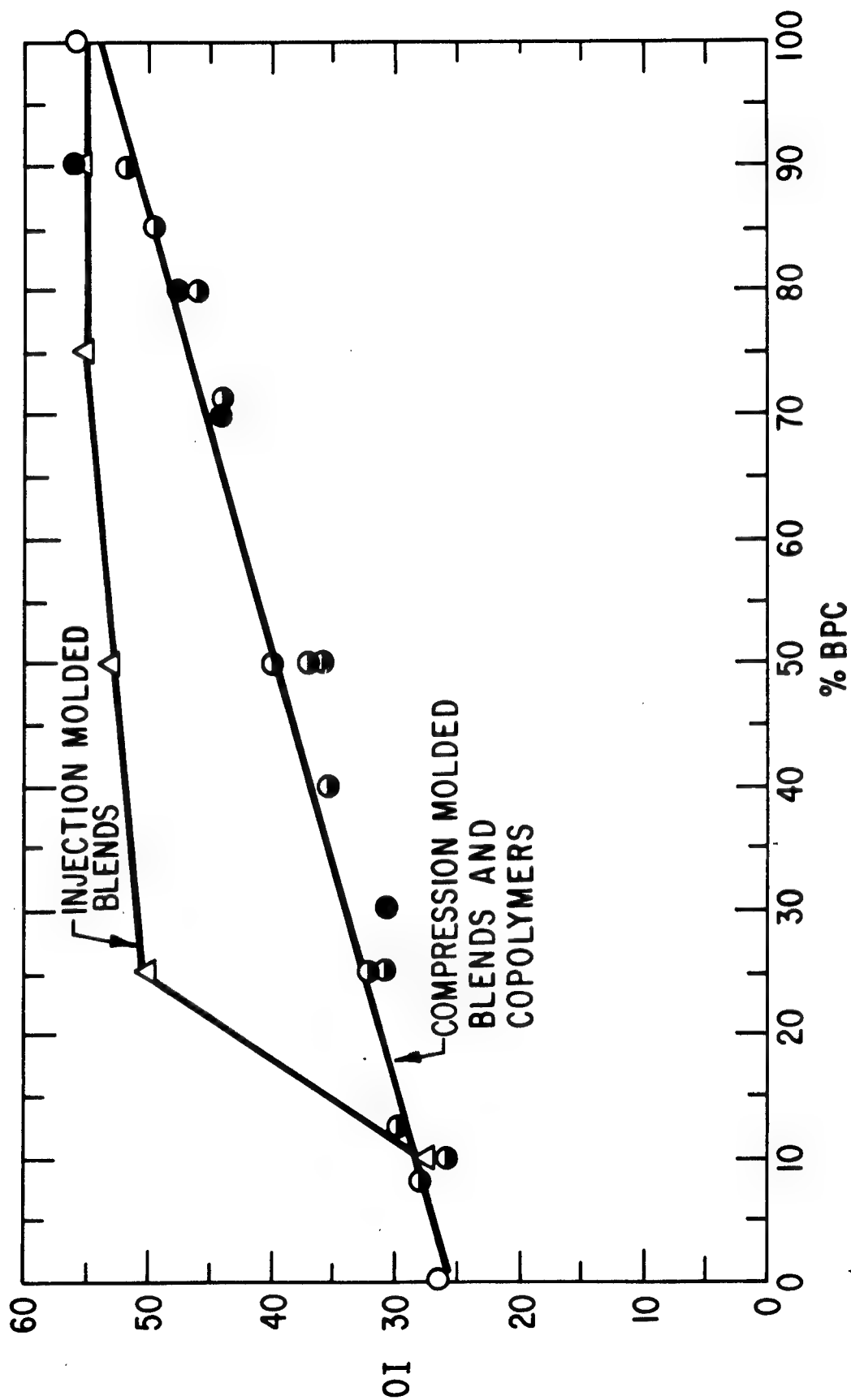


Figure 2. Oxygen Indexes of BPC/BPA Compositions; Δ Homopolymers, \bullet Copolymers, \bullet Blends - Compression Molded and Δ Blends - Injection Molded.

Table IX

Properties of BPC-PC/BPA-PC Structural Foams[†]

| Composition (BPC/BPA) | [η] (dl/g) | Density (g/cc) | Density Reduction | Impact (ft-lbs) | I _s ^a (1/4") | | OI | D _m (corr) ^b |
|--------------------------|----------------------|-------------------|----------------------|--------------------|------------------------------------|-------|------|------------------------------------|
| | | | | | Lab.A | Lab.B | | |
| 10/90 | 0.51 | 1.03 | 19% | >75 | 6.9 | 25 | 52.4 | 335 |
| 20/80 | 0.51 | 1.05 | 18% | >75 | 5.6 | 20 | 53.6 | 393 |
| 50/50 | 0.45 | 1.00 | 25% | >50 | 3.9 | -- | 54.8 | 284 |
| 80/20 ^c | -- | -- | -- | 20-25 | -- | 2.1 | -- | 31 |
| 100/0 | 0.34 | 1.07 | 24% | 25-37.5 | 0.8 | -- | 57.6 | 36 |

^aASTM E162 Radiant Panel Test.^bNBS smoke chamber, flaming mode.^cProduced by combining 85/15 copolymer with BPA-PC and blowing agent.[†]The flame tests described are not intended to reflect hazards presented by these or any other materials under actual fire conditions.

Toxicological Studies

Analyses have been performed on both the acute toxicity of BPC-PC and the acute and subacute toxicities of its monomer and its intermediate by the International Research and Development Corp., Mattawan, Michigan. The results of these tests along with related data from the literature are summarized in Table X. Based on the data obtained it was concluded that BPC-PC would not be considered a toxic material by the oral route of administration. As indicated in Table X, the monomer and its trichloro intermediate do show some physiological responses which appear to be similar to effects obtained with other phenolic materials.

As a follow-up to this work both the monomer and its trichloro intermediates were examined in the Ames mutagenicity test by the Litton Bionetics Testing Laboratory, Kensington, Maryland. In both cases in vitro assays showed negative mutagenic responses in six standard tester strains, with or without rat liver activation.

Biodegradation of BPC

The critical step in the biodegradability of a polyester is the biodegradation of the monomer produced by polymer hydrolysis. Thus, a study was made of the biodegradation of BPC (17) by activated sewage sludge obtained from a local sewage treatment plant, using a procedure developed to study the biodegradation of detergents (18). These studies indicate that this bisphenol is relatively easily biodegraded and that the rate of biodegradation is greatly increased by the presence of added nutrients, e.g., an ~9 day half life was observed with nutrients versus a 70 day half-life without.

Burn Gas Toxicity

The chemical composition of the burn gases of BPC-PC's has been determined and will be reported elsewhere (19). However, the most reliable method currently used to assess the potential toxic effect of burning materials is the use of animals as chemical "integrators". Thus tests were conducted by the Southern Research Institute of Birmingham, Georgia using rats in an air pyrolysis technique (20) at 500°C; a temperature which previous experience had shown halogenated materials to be relatively the most toxic. The results of this work, summarized in Table XI, shows the BPC-PC to be the least toxic of the polymers tested. The study also indicates that even though quantities of HCl were formed (~200 - 1200 ppm), the observed deaths were probably due to the CO present. Comparison of the chlorine analysis of char and the amount of HCl detected indicates that >90% of the Cl was unaccounted for. This could be due to the formation of condensed HCl or organic chlorides.

Table X

Summary of Toxicology Studies

| Subacute Toxicity Assays | | | | |
|--|-----------------------------------|--|--|---|
| Compounds | Oral LD ₅₀ (animal) | Other | | |
| | | 28 Day Dermal (Rabbits) | 28 Day Inhalation (Rats-2,10,20 mg/L) | Other |
| BPC Polycarbonate | >5.0g/kg (rat) | | | |
| 2,2-dichloro-4,4-bis(hydroxyphenyl)ethylene | 0.5-5.0 g/kg (rat) | Not acutely toxic dermally (rabbit). Not acutely toxic in 5 day rat inhalation (25 mg/L) | No Effect | Dose regulated pharmacological response; inhibition of body weight gain, decrease in food consumption, compound related effects on urinary tract, some mortality. |
| 2,2,2-trichloro-4,4-bis(hydroxyphenyl)ethane | >5.0 g/kg (rat) | Not acutely toxic dermally (rabbit). Not acutely toxic in 5 day rat inhalation (35 mg/L) | No Effect | Dose related pharmacological response similar to dichloro bisphenol no mortality. |
| BPA | 2-4 g/kg (rat) | LD _{LO} ^a (oral,mus) 600 mg/kg ^b | | 15-86 rats of weight days a central and low globin throy |
| Phenol | 0.4-1.3 g/kg (rat) | LD _{LO} ^a (man) 140 mg/kg | | Prolonged vapors induce diffic damage and pa |

a) LD_{LO} (lowest dose showing lethality).

b) 1976 NIOSH Registry of Toxic Effects of Chemical Substances.

a) LD₅₀ (lowest dose showing lethality).

b) 1976 NIOSH Registry of Toxic Effects of Chemical Substances.

c) Hygenic Guide Series.

d) Chapt. XXXIII, Patty et al, "Industrial Hygiene and Toxicology", J. Wiley and Sons, Inc. (1963).

TABLE XI

Inhalation Toxicity of the 500°C Pyrolysis Products of Materials

| <u>Polymer</u> | ALC_{50}^a (gm burned) | ALC_{50}^a (gm burned - char) | CO (ppm at ALC_{50}) |
|--------------------------------------|-----------------------------|------------------------------------|----------------------------|
| 85/15 BPC/BPA Copolymer ^b | 83.6 | 39.7 | 4700 |
| BPA-PC | 32.0 | 25.3 | 5213 |
| FR ABS (20% Cl as PVC) | 21.7 | 18.1 | 3800 |

^a ALC_{50} is the amount of test material required to achieve 50% mortality under the conditions of the test.

^bStabilized (21)

It is significant that the 85/15 BPC/BPA copolycarbonate was less toxic than the BPA-PC; because similar air pyrolysis work has been published (22) where BPA-PC was ranked as one of the least toxic of ~30 samples of synthetic and natural materials tested. Thus this test indicates that BPC-PC's may be the least toxic as well as the least flammable and least smoky of the known thermoplastics. Nonetheless, further toxicity testing with different endpoints, temperature, etc. is still necessary before the relative toxicity of BPC-PC is fully known.

CONCLUSIONS

Evaluation of the properties of polycarbonates made from BPC and BPA indicate that both the copolymers and the blends of the homopolycarbonates of the two different bisphenols result in transparent thermoplastics possessing nearly the same attractive physical properties as the homopolycarbonate from bisphenol A. In addition, many of these formulations possess flame resistant properties exceeding those of other transparent thermoplastics, e.g., highest OI, lowest smoke and lowest ratings in the ASTM E84 tunnel and E162 radiant panel tests. In addition, preliminary bioassay results with rats of the products from 500°C air pyrolysis gives an LD₅₀ value greater than that of other common thermoplastics.

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THE USE OF THE USF-NASA TOXICITY SCREENING TEST METHOD

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ABSTRACT

The USF-NASA toxicity screening test method is primarily intended to indicate which materials are more toxic under specific test conditions, and not necessarily to explain why they are more toxic. Analysis of the test data obtained, however, in the light of the experience accumulated, can provide some insight into the mechanisms of toxicity and the importance of specific toxicants.

The use of free-field movement offers both advantages and disadvantages relative to other behavioral paradigms, and the use of Swiss Webster mice offers both advantages and disadvantages relative to other species and strains.

INTRODUCTION

It is generally accepted that no single test or set of test conditions can adequately predict the performance of a material in all fire situations. Variables such as temperature, heat flux, air flow rate, and geometry combine to create an infinite number of possibilities. Toxicity testing itself introduces still another set of variables to make the problem even more complex.

Because of the need to evaluate materials at as many relevant test conditions as possible, cost-effectiveness in screening materials dictates that each test be as simple as possible so that as many conditions as possible can be investigated. Unfortunately, many proposed protocols have become so complicated for the sake of science that it has become economically prohibitive to vary test conditions as much as is indicated by common sense.

The toxicity screening test method developed at the University of San Francisco with the support of the National Aeronautics and Space Administration was intended to indicate which materials were more toxic under specified sets of test conditions, and not necessarily explain why they were more toxic (18). The USF-NASA procedure uses the bioassay approach in that it simply uses the laboratory animal as the integrator of all the concentration-time effects of the individual toxicants.

CHOICE OF ANIMAL MODEL

A large number of animal models are available for studies seeking to predict the effects of toxicants on man. These include the mouse, rat, guinea pig, rabbit, dog, and monkey. Increasing size is generally accompanied by increasing cost of acquisition

and husbandry, increasing size of chamber and facility requirements, and increasing amount of the sample material required to generate the needed toxicants. For samples which are not available in large quantities to start with, such as experimental materials, the smaller species are favored out of sheer necessity.

The two species of laboratory animals which are used for the majority of fire toxicity studies are the mouse and the rat. Each species has its advantages and disadvantages; each species has its proponents among toxicologists, physiologists, and pathologists. The mouse costs one-fifth as much and weighs one-tenth as much as the rat, and has proportionately smaller requirements in terms of chamber size, facility size, and maintenance cost. The mouse is more spontaneously active and permits the use of free-field movement as a behavioral paradigm, eliminating the need for motor-driven rotorods and rotating cages and electrically powered shock-avoidance techniques which introduce additional variables. As a significantly smaller animal, the mouse permits a significantly larger number of animals to be exposed in a given chamber size, thereby improving the statistical base.

The mouse has a disadvantage in that the small blood volume does not permit multiple sampling of blood for hematological studies. A technique for extracting sufficient blood in one sample has been developed (9), but this technique requires sacrifice of the animal and does not permit repeated sampling from the same animal.

CHOICE OF EXPOSURE CHAMBER

The animal exposure chamber is of a design developed and patented by the National Aeronautics and Space Administration (10), and has been extensively used in oxygen toxicity studies involving free-moving mice (11). The chamber is made of clear polymethylmethacrylate, facilitating continuous observation of the animals during the test. The hemispherical design provides a minimum of dead space, and the spontaneous activity of the mice seems to result in fairly uniform distribution of the gases throughout the chamber volume.

The chamber has a diameter of 203 mm (8 in) and a volume of 4.2 L. It occupies relatively little bench space and requires a relatively small volume of gases. The polymethylmethacrylate is superior to glass in ease of fabrication and repair, light weight, resistance to shock, and inertness to fluorides, which are pyrolysis effluents from some synthetic polymers.

The upper dome section is removable, and is connected to the base section by means of a conventional toggle snap ring; the joint is sealed by an O-ring. The toggle snap feature provides rapid assembly and disassembly, permitting removal of the animals within seconds if necessary. Under certain overpressure conditions, the toggle snap has opened and served as a safety pressure release valve.

CHOICE OF BEHAVIORAL PARADIGM

Free-field movement permits the observation of natural, unrestrained behavior which can be understood and recorded by the average layman. Exploratory, grooming, and escape behavior can be observed and evaluated, features which are eliminated in the rotorod, rotating cage, and some shock-avoidance techniques. The rate of oxygen consumption, and the accompanying intake of toxicants, are determined by natural animal response, and not an artifact imposed by enforced activity.

The animal responses which are routinely recorded are staggering, convulsions, collapse, and death.

Time to staggering is defined as the time to the first observation of loss of equilibrium or uncoordinated movement in a specific test animal. This response is a measure of effect on motor equilibrium.

Time to convulsions is defined as the time to the first observation of uncontrolled muscular movements in a specific test animal. This response is a measure of the effect on the central nervous system.

Time to collapse is defined as the time to the first observation of loss of muscular support in a specific test animal. This response is a measure of the effect on the muscular system.

Time to death is defined as the time to the observed cessation of movement and respiration in a specific test animal. This response is the classic response of traditional toxicology.

All of these responses are determined by visual observation and recorded. The precision of the recorded times is excellent for test operators who have had satisfactory experience.

CHOICE OF NUMBER OF ANIMALS

A completely closed system represents the most severe situation with regard to oxygen depletion because of oxygen consumption by the test animals. The small size of the test animals, 25 to 40 g body weight, and the small volume of the chamber, 4.2 L, represent the boundary conditions for balancing number of animals against oxygen depletion.

Four animals is considered to be the minimum required for adequate statistical treatment, as well as the largest number which can be satisfactorily observed by a single operator. Four provides a significant statistical advantage over three.

In control experiments without toxicants and using four mice in a completely closed system, oxygen concentrations decreased to about 16 per cent after 15 minutes and about 12 per cent after 30 minutes (12); in actual experiments with pyrolysis gases containing toxicants, however, oxygen concentrations decreased to about 17 per cent after 15 minutes and about 16 per cent after 30 minutes. This difference is attributed to reduced respiration rate because of sensory irritation, and, in the latter stages of the exposure, reduced oxygen consumption because of death of animals. For practical purposes, oxygen concentrations do not generally fall below 16 per cent in toxicity tests, and tend to remain above 18 per cent with the shorter times to death. In any event, oxygen concentrations as low as 12 per cent have not had significant effects in some mouse studies (13).

The flow-through system provides much higher levels of oxygen in the exposure chamber, and six mice could be exposed at the same time if observed by a more experienced test operator. Under these conditions, one effect of increasing the number of animals is an increase in chamber temperature due to body heat from the animals. The body heat from four mice raises the temperature in the chamber by about 2°C., and six animals would increase this temperature rise to about 3°C.

CHOICE OF TEST CONDITIONS

With a relatively low cost per experiment, the use of different test conditions becomes more feasible. For the baseline test conditions, a rising temperature program

at 40°C/min from 200°C to 800°C was selected because this permitted toxicants evolved over a range of temperatures to be represented; a closed system was selected to prevent escape of toxicants and provide a cumulative effect. This set of baseline conditions, identified as Procedure B, was used to evaluate over 300 materials.

Other options which have been used, of course with smaller numbers of materials, were the fixed temperature program and the flow-through system. The fixed temperatures were for the most part 300°C, 400°C, 500°C, 600°C, 700°C, and, most frequently, 800°C. Intermediate temperatures at 50°C increments were sometimes used to focus on certain temperature ranges. The flow-through system involved air flow rates of 1 and 3 L/min, levels which were largely determined by the capabilities of the pumps available.

PRECISION

Any biological study involving laboratory animals entails unavoidable variation among individual test animals. Variation among the humans which these animals seek to predict is certainly greater, because humans are not bred and raised under such controlled conditions. The USF-NASA procedure requires a minimum of two experiments, each involving four animals. Reproducibility is excellent; the standard deviation between the means of the individual experiments for time to death is generally less than 10 per cent, and is sometimes so small as to be difficult to believe. For example, the first experiment with a certain polyester urethane flexible foam gave individual animal times to death of 18.30, 21.07, 17.75, and 17.08 min, and a mean of 18.55 ± 1.75 min. The second experiment with this same material, with two experiments on other materials intervening, gave individual animal times to death of 19.12, 18.67, 17.83, and 18.58 min, and a mean of 18.55 ± 0.53 min.

For a polycarbonate reference material used in 41 replicate experiments involving 164 animals, the standard deviations between experiments were 13.2 per cent for staggering, 9.3 per cent for convulsions, 10.7 per cent for collapse, and 9.9 per cent for death (14).

COMPARISON WITH OTHER MATERIALS

One of the advantages offered by the USF-NASA toxicity screening test method is the ability to compare test results on any material with available data on over 300 materials which have been previously tested. When the composition of the sample is proprietary, this permits comparison with other materials to detect possible effects of chemical composition without disclosing proprietary information by identifying the materials selected for comparison.

MECHANISMS OF THERMAL DECOMPOSITION

Because the rising temperature program of Procedure B specifies a furnace temperature of 200°C at the start, 400°C at 5 min, 600°C at 10 min, and 800°C at 15 min, any observations recorded at specific times provide an indication of the temperatures related to those phenomena.

For example, a yellow smoke observed in the pyrolysis tube or exposure chamber at 7.5 min would indicate that the chemical decomposition reactions producing this yellow smoke occurred at a temperature below 500°C. Convulsions in the test animals occurring at 10 min would indicate the toxicants in sufficient concentrations to cause these convulsions were produced by chemical decomposition reactions occurring at temperatures below 600°C.

ROLE OF CARBON MONOXIDE

Gas samples of the chamber atmospheres are taken at the time of death of the last surviving animal, and analyzed for carbon monoxide by means of gas chromatography. Because these analyses are essentially isolated spot values which provide no information about concentration trends, only limited conclusions can be based on these data. However, because a closed system is used to prevent escape of toxicants, it seems reasonable to assume that the carbon monoxide concentrations are the highest encountered by the test animals.

Comparison of these carbon monoxide concentrations and the corresponding times to death with a reference curve permits reasonable deductions with regard to the importance of the role of carbon monoxide. This reference curve was developed from exposures of Swiss Webster mice in the 4.2 L chamber to known concentrations of carbon monoxide, to give times to death which take into account any effects of oxygen depletion and carbon dioxide accumulation (15).

If mice die during the exposure and the carbon monoxide concentration at the end of the test is less than 3,000 ppm, carbon monoxide could not have been the sole toxicant.

If the carbon monoxide concentration at any specific time to death is less than the carbon monoxide concentration corresponding on the plot to that period of exposure, carbon monoxide could not have been the sole toxicant.

A limited number of experiments on representative materials provide a basis for approximating the concentration-time exposure of the animals to carbon monoxide, based on the carbon monoxide concentrations at the end of the test (16,17). The concentration-time product or death-product (DP) value for carbon monoxide in tests using the fixed temperature program is approximately $(ct)_f/2$, where c is the concentration of carbon monoxide in ppm, t is the elapsed time in min, both at the time of death of the last surviving animal, and DP is in ppm-min (16). The DP value using the rising temperature program is approximately $(ct)_f/4$, on the same basis (17). If the DP value exceeds 45,000 ppm-min, carbon monoxide was present in sufficient concentration for sufficient time to have been the sole toxicant. If the DP value is between 30,000 and 45,000 ppm-min, carbon monoxide may have been the principal toxicant. The value of 45,000 ppm-min is a consensus of the 40,000 ppm-min reported by Saito (18) and the 47,200 ppm-min reported by Hilado and Cumming (15).

MECHANISMS OF TOXICITY

The individual animal responses provide some insight into the mechanisms of toxicity, because of the patterns which have been observed in the course of accumulating experience with so many materials. It should be emphasized that the animal responses discussed are the responses defined earlier in this paper. The following statements would not necessarily be valid for other test methods with different definitions of these responses.

In the case of materials from which carbon monoxide is the principal toxicant, collapse is preceded by convulsions and followed some minutes later by death.

In the case of materials from which chlorine-containing gases are important toxicants (such as polyvinyl chloride), convulsions are observed after collapse.

In the case of materials from which sulfur-containing gases are important toxicants (such as sulfone and sulfide polymers), death occurs within one minute after collapse.

If an animal which is alive at the end of a 30 min exposure survives for two days afterwards, nitrogen dioxide intoxication is probably not a significant factor.

If an animal which is alive at the end of a 30 min exposure survives for 14 days afterwards, carbon monoxide was probably the principal factor causing the responses observed during the exposure.

CONCLUSIONS

The USF-NASA toxicity screening test method appears to be a useful means of screening materials on a cost-effective basis. Its limitations as a smallscale laboratory procedure, however, should be understood.

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APPENDIX

APPARATUS

A Lindberg horizontal tube furnace is used for pyrolysis. The sample material is pyrolyzed in a quartz boat centered in a quartz tube, closed at one end with a cap and connected at the open end to the animal exposure chamber.

The animal exposure chamber (Figure 1) is of a design developed and patented by NASA and is made of clear polymethyl methacrylate so that continuous observation of the animals is facilitated. The activity of the free moving mice in the chamber allows observation of natural, unrestrained behavior which can be recorded by the average lay person. This spontaneous activity appears to result in fairly uniform distribution of the gases throughout the chamber volume.

The polymethyl methacrylate is superior to glass in ease of fabrication, light weight, resistance to shock, and inertness to hydrogen fluoride, which is a pyrolysis effluent from some synthetic polymers. The chamber has a total free volume of 4.2 liters, and is made of an upper dome section and a lower base section, both with a diameter of 203 mm (8 in).

The upper dome section is removable, and is connected to the base section by means of a conventional toggle snap ring; the joint is sealed by an O-ring. Access to the chamber is provided by two horizontal cylinders of different diameter mounted on the dome section. The larger horizontal cylinder, having a diameter of 59 mm (2.38 in), is fitted with an adapter to accomodate the open end of the pyrolysis tube. The smaller horizontal cylinder, having a diameter of 39 mm (1.56 in), is fitted with an adapter to accomodate the probe of a Beckman process oxygen analyzer, and serves also as the entry port for the test animals. A perforated polymethyl methacrylate plate across the larger horizontal cylinder prevents movement of the mice into the pyrolysis tube.

The upper end of the dome section is provided with apertures and a clear polymethyl methacrylate cylinder having a cover plate; the cover plate is connected to a bubbler to permit venting of pressure exceeding 25 mm (1 in) of water and prevent entry of fresh air, and is provided with fittings for a thermometer and for gas sampling.

PROCEDURE

The pyrolysis tube, pyrolysis boat, animal exposure chamber, and all fittings and adapters are thoroughly cleaned and dried before each test. The pyrolysis boat is weighed without and with the sample under test. A sample weight of 1.00 g is normally used for screening studies, and was used in this study.

The test animals are received in plastic cages, with each test group in its own cage. Each animal is removed, inspected for freedom from abnormalities, weighed, and marked on some part of the body with different colors of ink for identification. Four Swiss-Webster male mice, 25 to 40 g body weight, are used for each test. Four appears to be the optimum number of mice which can be used for each test without excessive oxygen consumption during the test period, as well as the largest number which can be satisfactorily observed by a single operator.

Each experiment is repeated two or more times. This replication provides measures of variation between test animals and between experiments.

The mice are placed in the animal exposure chamber and given a minimum of 5 min to accustom themselves to their surroundings. The entire system is sealed (except for the safety vent) and all joints are checked for proper seating. The pyrolysis tube containing the sample is introduced into the furnace, which is preheated to 200°C in the case of the rising temperature program, or 800°C in the case of the fixed temperature program. In the case of the rising temperature program, the furnace is turned on at the start of the test at the predetermined heating rate of 40°C/min; when the furnace approaches or reaches 800°C, this temperature is maintained by either automatic or manual control until the end of the test. The test period is 30 min, unless 100% mortality occurs earlier; the test is terminated upon the death of the last surviving animal, and any samples for gas analysis are taken at that time before the system is opened.

Time to first sign of incapacitation is defined as the time to the first observation of loss of equilibrium (staggering), prostration, collapse, or convulsions in any of the test animals.

Time to staggering is defined as the time to the first observation of loss of equilibrium or uncoordinated movement in a specific test animal.

Time to convulsions is defined as the time to the first observation of uncontrolled muscular movements in a specific test animal.

Time to collapse is defined as the time to the first observation of loss of muscular support in a specific test animal.

Time to death is defined as the time to the observed cessation of movement and respiration in a specific test animal.

Temperatures in the breathing zone of the animal exposure chamber are recorded at 1-min intervals throughout the entire test period.

After the test is terminated and the animals are removed from the chamber, the pyrolysis boat containing the sample is removed, allowed to cool, and weighed to permit calculation, by difference, of the weight of sample pyrolyzed. If all the test animals die during the test, the pyrolysis boat is removed before the animals are removed, to minimize additional weight loss. Surviving animals are observed for a 14-day period after the test, and any significant changes from normal appearance or behavior are noted.

For test conditions requiring controlled air flow instead of a completely closed system, a nominal air flow of 1 L/min is obtained by pumping a continuous flow of air into the normally closed end of the pyrolysis tube, using a Hush I aquarium pump (Metaframe Corporation).

Gas samples of the chamber atmospheres are withdrawn in 60 ml syringes, and are analyzed by means of gas chromatography.

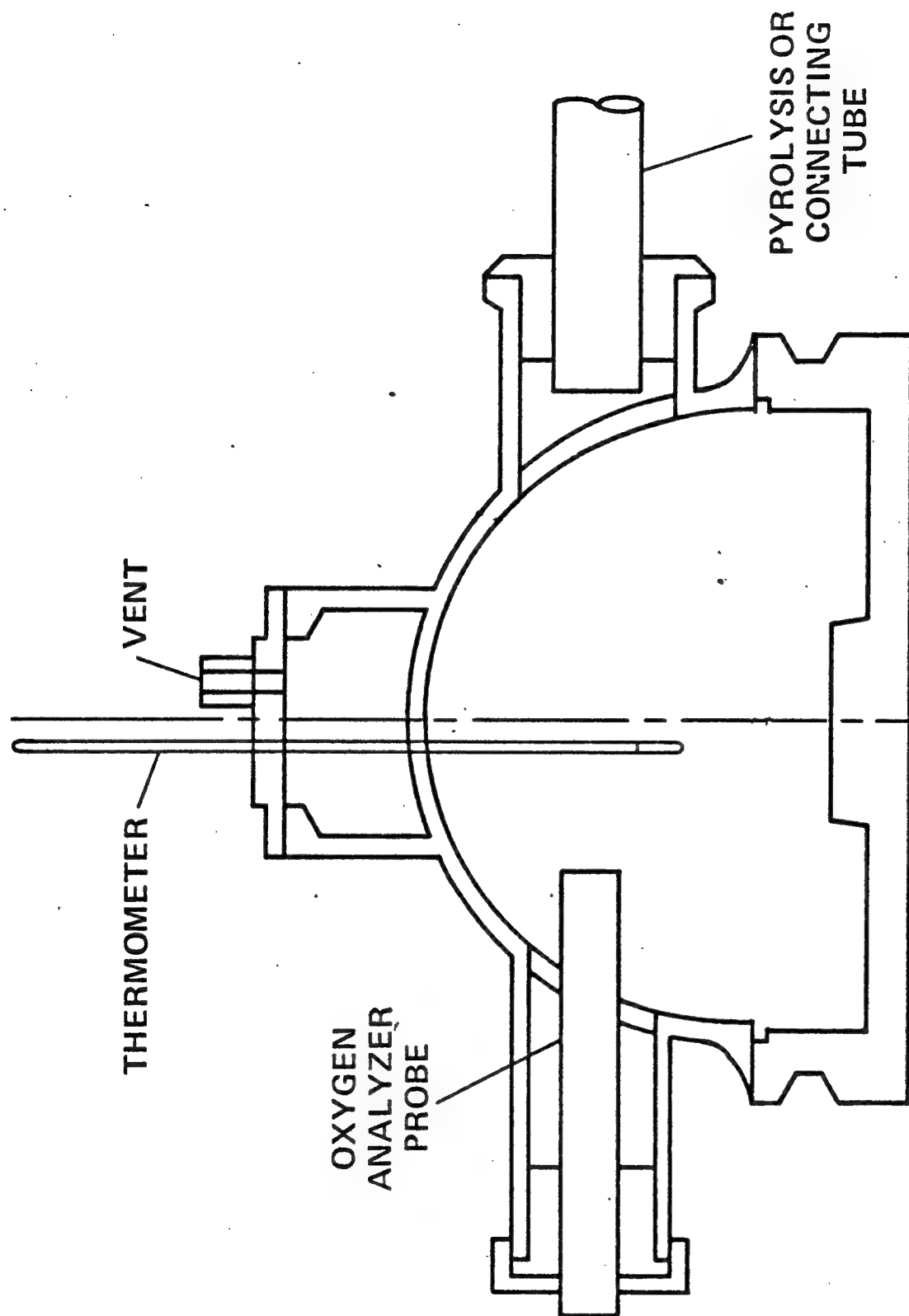


Figure 1. Animal Exposure Chamber

Table 1. Relative toxicity data using USF procedure B 200-800 C rising temperature, 40 °C min⁻¹, no forced air flow^a

| Material | Time to death (min) | Time to incapacitation (min) | No. of tests | No. of animals |
|--|---------------------|------------------------------|--------------|----------------|
| Modacrylic/rayon 70/30 fabric | 4.54±1.00 | 3.74±0.23 | 2 | 8 |
| Wool/spandex 99/1 fabric | 5.80±0.42 | 4.52±0.13 | 2 | 8 |
| Wool fabric, 100%, 2 | 6.47±0.23 | 5.06±0.69 | 2 | 8 |
| Nylon fabric, 20/80 polyurethane foam/acrylic back | 6.72±0.73 | 5.55±0.47 | 2 | 8 |
| Wool fiber, washed | 7.06±1.18 | 4.82±1.01 | 2 | 8 |
| Feathers/down 75/25 | 7.26±0.12 | 5.12±0.36 | 2 | 8 |
| Wool/nylon 90/10 fabric | 7.59±1.36 | 5.08±0.60 | 3 | 12 |
| Wool fabric, 100%, 1 | 7.60±2.90 | 5.45±1.77 | 4 | 16 |
| Rubberized hair, FR | 7.62±0.83 | 4.42±0.36 | 2 | 8 |
| Rubberized hair | 8.18±0.50 | 5.82±0.28 | 2 | 8 |
| Wool fabric, 100%, treated | 8.24±1.84 | 6.28±1.45 | 4 | 16 |
| Wool/nylon 88/12 fabric | 8.92±3.13 | 5.06±1.58 | 3 | 12 |
| Wool/nylon 86/14 fabric | 8.93±1.06 | 5.34±0.83 | 2 | 8 |
| Silk fabric, 100% | 8.94±0.01 | 5.84±0.12 | 2 | 8 |
| Polyurethane flexible foam, 1.75 pcf, E3 | 9.14±0.25 | 7.50±0.67 | 2 | 8 |
| Polyester fabric, 100% | 9.36±0.45 | 7.38±0.18 | 2 | 8 |
| Silk fabric, 100% | 9.43±1.64 | 7.56±1.64 | 2 | 8 |
| Polyester batting, without resin | 9.44±0.76 | 8.21±0.44 | 2 | 8 |
| Wool fabric, 100%, reference | 9.46±1.59 | 5.92±1.46 | 2 | 8 |
| Cotton batting, 2 | 9.66±1.29 | 5.90±0.04 | 2 | 8 |
| Polyurethane flexible foam, 1.45 pcf, E2 | 9.86±0.92 | 8.30±0.25 | 2 | 8 |
| Wool/nylon 85.4/14.6 fabric | 10.05±1.39 | 7.26±1.75 | 2 | 8 |
| Rayon/cotton 75/25 fabric | 10.06±0.81 | 7.23±0.78 | 2 | 8 |
| Polyurethane flexible foam, 1.20 pcf, E1 | 10.06±0.28 | 8.90±0.53 | 2 | 8 |
| Rayon/cotton 61/39 fabric | 10.12±1.89 | 8.02±0.70 | 2 | 8 |
| Polyester batting, 13.3% acrylic resin | 10.15±0.64 | 8.55±0.52 | 2 | 8 |
| Polyurethane flexible foam, 1.80 pcf, D1 | 10.16±0.68 | 8.45±0.40 | 3 | 12 |
| Cotton batting, 1 | 10.16±0.43 | 6.74±0.90 | 2 | 8 |
| Leather | 10.22±1.72 | 8.16±0.69 | 2 | 8 |
| Polyether sulfone, 300-P | 10.26±0.32 | 9.63 | 1 | 4 |
| Rayon/cotton 75/25 fabric | 10.28±0.81 | 7.40±1.09 | 2 | 8 |
| Cotton batting, FR | 10.44±0.95 | 7.93±1.20 | 2 | 8 |
| Polyester batting, 20.6% acrylic resin | 10.54±1.28 | 8.90±0.89 | 2 | 8 |
| Polyphenylene sulfide, 3 | 10.57±1.40 | 9.59±1.30 | 4 | 16 |
| Polyurethane rigid foam, 10% FR, R2 | 10.62±1.10 | 8.28±1.39 | 2 | 8 |
| Polyester/acetate 65/35 fabric | 10.63±0.20 | 7.76±0.11 | 2 | 8 |
| Polyester/acetate 65/35 fabric | 10.65±0.14 | 7.40±0.61 | 3 | 12 |
| Rayon/cotton 64/36 fabric | 10.78±1.72 | 7.99±0.75 | 3 | 12 |
| Hemlock, untreated | 10.80±0.18 | 7.28±2.03 | 2 | 8 |
| Cotton/acetate/nylon/polyester 55/23/19/3 fabric | 10.84±0.35 | 7.83±0.74 | 3 | 12 |
| Hardboard, unfinished | 10.86±0.54 | 8.56±0.37 | 2 | 8 |
| Rayon/cotton/nylon 63/27/10 fabric | 10.91±0.65 | 8.31±0.15 | 2 | 8 |
| Cotton/nylon 73/27 fabric | 10.94±0.94 | 7.88±0.09 | 2 | 8 |
| Polyimide foam, modified | 11.02±0.62 | 9.04±0.47 | 2 | 8 |
| Polyphenylene sulfide, 1 | 11.07±1.65 | 10.22±1.80 | 2 | 8 |
| Polybismaleimide | 11.12±0.11 | 9.60±0.14 | 2 | 8 |
| Polyurethane flexible foam, FR, 1.80 pcf, D2 | 11.18±0.74 | 9.20±0.97 | 3 | 12 |
| Cotton batting, FR, 8% boric acid | 11.20±1.25 | 8.21±0.06 | 2 | 8 |
| Polyaryl sulfone, 1 | 11.23±1.48 | 10.01±1.35 | 3 | 12 |
| Rayon/cotton/acetate/nylon 43/25/23/9 fabric | 11.37±0.35 | 6.65±2.39 | 2 | 8 |
| Rayon/cotton/acetate/polyester 73/16/6/5 fabric | 11.40±0.92 | 9.10±0.38 | 2 | 8 |
| Rayon/cotton 59/41 fabric | 11.47±1.12 | 7.92±2.13 | 2 | 8 |
| Red oak, 2 | 11.50±0.71 | 8.09±1.00 | 2 | 8 |
| Rayon/cotton 68/32 fabric | 11.57±0.31 | 5.68±0.21 | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 1.45 pcf, E5 | 11.73±0.03 | 9.13±1.24 | 2 | 8 |
| Rayon/cotton 64/36 fabric | 11.75±2.51 | 8.46±1.57 | 2 | 8 |
| Particle board, untreated | 11.82±0.04 | 9.32±0.39 | 2 | 8 |
| Cotton/nylon 82/18 fabric | 11.89±0.95 | 8.46±0.94 | 2 | 8 |
| Cotton fabric, 100% | 11.90±1.63 | 7.10±0.14 | 2 | 8 |
| Silk/nylon 70/30 fabric | 11.92±0.14 | 8.95±0.66 | 2 | 8 |
| Cotton/nylon 63/37 fabric | 11.94±3.61 | 6.30±2.75 | 2 | 8 |
| Cotton/nylon 53/47 fabric | 11.96±0.38 | 8.33±1.76 | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 1.40 pcf, F1 | 12.03±1.29 | 10.25±1.64 | 4 | 16 |
| Rayon/cotton/nylon 41/36/23 fabric | 12.09±1.90 | 9.34±1.23 | 2 | 8 |
| Cotton/nylon 86/14 fabric | 12.11±2.07 | 9.61±1.46 | 2 | 8 |

Table 1. Relative toxicity data using USF procedure B 200-800 °C rising temperature, 40 °C min⁻¹, no forced air flow^a

| Material | Time to death (min) | Time to incapacitation (min) | No. of tests | No. of animals |
|--|---------------------|------------------------------|--------------|----------------|
| Rayon/acetate/olefin 62/19/19 fabric | 12.14 ± 1.06 | 7.71 ± 0.13 | 2 | 8 |
| Polyether sulfone, 212-P | 12.22 ± 1.52 | 10.72 ± 1.74 | 4 | 16 |
| Rayon/cotton/acetate/polyester 66/19/11/4 fabric | 12.22 ± 0.91 | 6.86 ± 0.65 | 2 | 8 |
| Rayon fabric, 100% | 12.31 ± 1.21 | 9.34 ± 0.55 | 2 | 8 |
| Cotton/acetate/rayon/nylon 61/25/11/3 | 12.37 ± 0.81 | 8.37 ± 0.81 | 2 | 8 |
| Rayon fabric, 100% | 12.39 ± 0.14 | 7.93 ± 1.86 | 2 | 8 |
| Polyphenylene sulfide, 2 | 12.40 ± 1.86 | 10.84 ± 1.89 | 2 | 8 |
| Rayon/cotton 73/27 fabric | 12.43 ± 1.67 | 8.41 ± 0.48 | 2 | 8 |
| Rayon/olefin 73/27 fabric | 12.55 ± 2.11 | 9.50 ± 0.11 | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 1.75 pcf, E6 | 12.57 ± 0.01 | 9.66 ± 1.33 | 2 | 8 |
| Sisal | 12.59 ± 3.41 | 6.43 ± 2.05 | 2 | 8 |
| Rayon/nylon 56/44 fabric | 12.62 ± 2.82 | 8.98 ± 2.17 | 2 | 8 |
| Rayon/acetate/cotton 31.49/26.80/41.71 fabric | 12.62 ± 2.54 | 7.46 ± 0.75 | 2 | 8 |
| Silk/rayon 70/30 fabric | 12.74 ± 1.15 | 8.94 ± 0.43 | 2 | 8 |
| Pigskin | 12.78 ± 0.77 | 7.16 ± 0.71 | 2 | 8 |
| Rayon fabric, 100% | 12.79 ± 1.32 | 8.48 ± 1.37 | 2 | 8 |
| Nylon fabric, 100% | 12.81 ± 0.94 | 9.40 ± 2.85 | 2 | 8 |
| Cotton/acetate 67/33 fabric | 12.90 ± 1.83 | 10.26 ± 2.45 | 2 | 8 |
| Rayon/cotton/acetate/nylon 57/23/11/9 | 12.96 ± 1.64 | 10.47 ± 0.17 | 2 | 8 |
| Polypropylene fabric, 100% | 12.98 ± 0.52 | 10.75 ± 0.18 | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 2.80 pcf, F5 | 13.01 ± 2.09 | 11.03 ± 2.00 | 4 | 16 |
| Polyurethane flexible foam, HR, FR, 2.80 pcf, H6 | 13.01 ± 0.11 | 10.32 ± 0.44 | 3 | 12 |
| Cotton fabric, 100% | 13.02 ± 0.93 | 8.54 ± 0.53 | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 1.45 pcf, F2 | 13.02 ± 0.89 | 11.20 ± 0.84 | 4 | 16 |
| Cotton fabric, FR, 2 | 13.06 ± 1.46 | 9.78 ± 2.55 | 2 | 8 |
| Cotton, surgical | 13.13 ± 1.51 | 9.61 ± 1.42 | 17 | 68 |
| Nylon fabric, 100% | 13.14 ± 0.49 | 10.65 ± 0.10 | 2 | 8 |
| Cotton fabric, 100% | 13.21 ± 1.37 | 10.48 ± 0.08 | 2 | 8 |
| Rayon/nylon/cotton 49/33/18 fabric | 13.28 ± 1.70 | 9.28 ± 0.31 | 3 | 12 |
| Nylon 6/10 | 13.28 ± 1.63 | 11.48 ± 1.59 | 2 | 8 |
| Polyester fabric, 100% | 13.30 ± 1.95 | 8.85 ± 3.25 | 2 | 8 |
| Polyurethane flexible foam, HR, FR, 2.70 pcf, H1 | 13.32 ± 0.95 | 10.74 ± 1.16 | 3 | 12 |
| Nylon 6 | 13.47 ± 1.13 | 11.55 ± 0.66 | 3 | 12 |
| Nylon fabric, 100% | 13.48 ± 0.72 | 10.87 ± 0.70 | 2 | 8 |
| Aromatic polyamide fabric, 1 | 13.50 ± 0.98 | 11.79 ± 1.71 | 2 | 8 |
| Polyurethane flexible foam, HR, FR, 2.60 pcf, H5 | 13.51 ± 1.29 | 10.27 ± 0.61 | 3 | 12 |
| Polyurethane flexible foam, 12% Fr, 2.50 pcf, F4 | 13.56 ± 4.57 | 10.50 ± 2.20 | 4 | 16 |
| Douglas fir, 2 | 13.62 ± 0.63 | 9.84 ± 0.12 | 2 | 8 |
| Polyester foam | 13.66 ± 0.67 | 7.50 ± 0.88 | 2 | 8 |
| Cotton fabric, 100% | 13.67 ± 3.16 | 8.69 ± 0.19 | 2 | 8 |
| Polyurethane rigid foam, 7% FR, R3 | 13.69 ± 1.44 | 10.91 ± 1.51 | 3 | 12 |
| Polyisocyanurate rigid foam | 13.74 ± 0.90 | | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 1.20 pcf, E4 | 13.74 ± 0.61 | 9.56 ± 2.57 | 2 | 8 |
| Polyester/rayon 54/46 fabric | 13.75 ± 0.99 | 8.89 ± 2.74 | 2 | 8 |
| Polyurethane flexible foam, HR, FR, 2.20 pcf, H4 | 13.79 ± 0.74 | 10.87 ± 1.34 | 3 | 12 |
| Beech | 13.82 ± 1.69 | 9.69 ± 0.84 | 3 | 12 |
| Cotton/rayon 59/41 | 13.86 ± 0.72 | 9.51 ± 0.12 | 2 | 8 |
| Polyurethane flexible foam, 12% FR, 2.00 pcf, F3 | 13.92 ± 1.06 | 11.41 ± 1.27 | 5 | 24 |
| Rayon fabric, 100% | 13.98 ± 2.92 | 10.06 ± 1.32 | 2 | 8 |
| Polyethylene, 1 | 13.99 ± 0.85 | 11.54 ± 0.62 | 3 | 12 |
| Polyurethane rigid foam, FR, Q1 | 14.05 ± 0.60 | 11.23 ± 0.50 | 3 | 12 |
| Aspen poplar | 14.06 ± 1.83 | 9.96 ± 1.66 | 3 | 12 |
| Polyurethane rigid foam, R1 | 14.10 ± 0.74 | 9.64 ± 2.31 | 2 | 8 |
| Rayon/cotton/nylon/polyester 54/24/16/6 fabric | 14.12 ± 2.60 | 8.30 ± 0.67 | 2 | 8 |
| Acetate/polyester 81/19 fabric, FR | 14.14 ± 3.89 | 6.14 ± 2.57 | 2 | 8 |
| Nylon/vinyon 70/30 fabric | 14.15 ± 1.68 | 10.85 ± 1.63 | 2 | 8 |
| Cotton/rayon/acetate 50/30/20 fabric | 14.22 ± 3.23 | 8.50 ± 0.33 | 2 | 8 |
| Acetate/rayon/cotton/polyester 48/28/15/9 fabric | 14.22 ± 3.07 | 10.02 ± 0.79 | 2 | 8 |
| Cotton fabric, 100% | 14.22 ± 2.14 | 8.94 ± 1.17 | 2 | 8 |
| Rayon/nylon/cotton 52/33/15 fabric | 14.23 ± 0.68 | 9.46 ± 0.05 | 2 | 8 |
| Cotton/polyester 50/50 fabric | 14.27 ± 0.17 | 9.18 ± 1.49 | 3 | 12 |
| Western hemlock | 14.37 ± 1.52 | 9.99 ± 0.40 | 3 | 12 |
| Cotton/rayon/acetate 55/39/6 fabric | 14.41 ± 5.04 | 9.53 ± 3.50 | 2 | 8 |
| Rayon/acetate/cotton 49/26/25 fabric | 14.41 ± 3.00 | 10.38 ± 0.58 | 2 | 8 |
| Polyether sulfone, 200-P | 14.42 ± 2.34 | 13.39 ± 2.28 | 2 | 8 |

Table 1. Relative toxicity data using USF procedure B 200-800 °C rising temperature, 40 °C min⁻¹, no forced air flow^a

| Material | Time to death (min) | Time to incapacitation (min) | No. of tests | No. of animals |
|--|---------------------|------------------------------|--------------|----------------|
| Polyurethane flexible foam, 2.80 pcf, H7 | 14.44±3.16 | 10.67±1.59 | 3 | 12 |
| ABS, 3 | 14.48±1.59 | 10.58±1.32 | 2 | 8 |
| Cotton/rayon/acetate 52/42/6 fabric | 14.49±2.01 | 9.84±3.02 | 2 | 8 |
| Red oak, 1 | 14.50±1.23 | 10.23±0.81 | 3 | 12 |
| Polyether sulfone 300-P/glass fabric | 14.54±0.23 | 12.74±0.74 | 2 | 8 |
| Cotton batting, FR, 10% boric acid | 14.58±1.06 | 9.94±2.92 | 2 | 8 |
| Rayon/nylon/acetate 41/30/29 fabric | 14.63±4.56 | 10.26±5.07 | 2 | 8 |
| Cotton/nylon/nylon/acetate 39/37/14/10 fabric | 14.63±1.37 | 8.44±2.27 | 2 | 8 |
| Rayon/cotton 71/29 fabric | 14.63±1.32 | 7.57±2.79 | 2 | 8 |
| Olefin/polyester 55/45 fabric | 14.64±1.72 | 9.14±0.36 | 2 | 8 |
| Rayon/acetate/cotton 65/25/10 fabric | 14.75±1.68 | 9.55±1.08 | 2 | 8 |
| Douglas fir, 1 | 14.76±0.90 | 11.79±0.90 | 3 | 12 |
| Cotton/polyester 59/41 fabric | 14.84±1.72 | 9.23±1.90 | 2 | 8 |
| Aromatic polyamide fabric, 2 | 14.89±2.11 | | 2 | 8 |
| Western red cedar | 14.91±3.18 | 10.00±0.97 | 3 | 12 |
| Polyethylene foam, 2 | 14.96±0.23 | 7.81±0.01 | 2 | 8 |
| Rayon/polyester 87/13 fabric | 15.01±2.27 | 6.90±2.51 | 2 | 8 |
| Polyurethane flexible foam, HR, 3.00 pcf, H8 | 15.07±2.59 | 9.84±0.78 | 3 | 12 |
| Cotton/nylon 75/25 fabric | 15.09±3.31 | 9.27±0.62 | 2 | 8 |
| Yellow birch | 15.09±2.57 | 9.56±0.97 | 3 | 12 |
| Cotton fabric, 100% | 15.10±3.03 | 9.18±3.61 | 2 | 8 |
| Polysulfone | 15.10±1.48 | 12.16±2.86 | 2 | 8 |
| Rayon fabric, 100% | 15.10±1.33 | 8.87±2.75 | 2 | 8 |
| Polyurethane flexible foam, HR, FR, 2.02 pcf, H2 | 15.11±1.95 | 9.85±3.18 | 3 | 12 |
| Rayon/acetate/cotton 55/30/15 fabric | 15.14±4.39 | 11.17±3.71 | 2 | 8 |
| Polyethylene foam, 1 | 15.14±1.94 | 8.44±1.94 | 2 | 8 |
| Polyurethane rigid foam, FR, 24.3 pcf | 15.14±0.62 | 12.62±1.24 | 2 | 8 |
| Cotton fabric, FR, 1 | 15.31±2.46 | 8.30±3.41 | 3 | 12 |
| FR vinyl/nylon 80/20 fabric | 15.32±0.78 | 12.56±2.42 | 2 | 8 |
| Cotton/nylon/nylon 67/30/3 fabric | 15.33±2.25 | 10.01±0.09 | 2 | 8 |
| Rayon/cotton 66/34 fabric | 15.40±3.57 | 12.17±2.12 | 2 | 8 |
| Eastern white pine | 15.42±0.90 | 10.72±0.85 | 3 | 12 |
| Acetate/nylon/cotton 35/33/32 fabric | 15.44±1.46 | 9.92±0.19 | 2 | 8 |
| Polyurethane flexible foam, FR, 3.00 pcf, H9 | 15.48±3.16 | 10.69±1.49 | 3 | 12 |
| Nylon/nylon 62/38 fabric | 15.52±0.19 | 11.99±0.36 | 2 | 8 |
| Southern yellow pine | 15.56±0.12 | 10.91±0.86 | 3 | 12 |
| Polymethyl methacrylate | 15.58±0.23 | 12.61±0.06 | 2 | 8 |
| Rayon/olefin 56/44 fabric | 15.60±5.14 | 11.85±1.73 | 2 | 8 |
| Vinyl, expanded, fabric | 15.64±0.95 | 7.69±0.48 | 2 | 8 |
| Polyaryl sulfone, 2 | 15.72±1.40 | 10.61±1.33 | 2 | 8 |
| Nylon/nylon 57/43 fabric | 15.73±5.79 | 12.36±3.58 | 2 | 8 |
| Aromatic polyamide fabric, 3 | 15.74±2.13 | 13.37±1.38 | 3 | 12 |
| Excelsior | 15.82±0.11 | 6.60±0.54 | 2 | 8 |
| Nitrile rubber, 2 | 15.85±0.97 | 9.50±0.16 | 3 | 12 |
| Polyvinylidene fluoride | 15.86±2.74 | 6.50±0.11 | 2 | 8 |
| Hardboard | 15.90±2.62 | 9.66±2.68 | 4 | 16 |
| Bisphenol A polycarbonate, 2 | 16.08±3.98 | 12.82±2.76 | 2 | 8 |
| Rayon/cotton 59/41 fabric | 16.08±0.81 | 10.18±2.05 | 2 | 8 |
| Kapok | 16.15±0.47 | 7.40±2.05 | 2 | 8 |
| Polyurethane flexible foam, HR, FR, 2.90 pcf, H3 | 16.25±2.11 | 11.05±2.04 | 3 | 12 |
| Acetate/cotton/polyester 52/37/11 fabric | 16.28±4.69 | 11.65±2.47 | 2 | 8 |
| Rayon fabric, 100% | 16.30±3.86 | 8.88±1.31 | 2 | 8 |
| Olefin fabric, 100% | 16.33±5.90 | 7.72±0.45 | 2 | 8 |
| Nylon fabric, 100% | 16.33±3.50 | 12.56±1.21 | 2 | 8 |
| Cotton/polyester 63/35 fabric, FR | 16.34±4.07 | 9.88±1.46 | 2 | 8 |
| Nylon 6/6 | 16.34±0.85 | 14.01±0.13 | 2 | 8 |
| Cotton/nylon 69/31 fabric | 16.37±3.54 | 11.85±0.96 | 2 | 8 |
| Polyvinyl chloride, 2 | 16.37±0.57 | 5.95±0.78 | 2 | 8 |
| Cotton/polyester 70/30 fabric | 16.49±1.90 | 9.04±0.45 | 2 | 8 |
| Asphalt saturated organic felt, 15 lb | 16.52±0.90 | 12.78 | 1 | 4 |
| Rayon/cotton 92/8 fabric | 16.56±4.56 | 12.77±3.40 | 2 | 8 |
| Cotton/nylon 67/33 fabric | 16.58±3.01 | 9.38±0.09 | 2 | 8 |
| Polyurethane flexible foam, 1.45 pcf, B1 | 16.60±1.14 | 10.21±0.86 | 2 | 8 |
| Nylon fabric, 100% | 16.69±0.06 | 11.69±1.37 | 2 | 8 |
| Cotton fabric, 100% | 16.78±2.25 | 8.72±1.31 | 4 | 16 |

Table 1. Relative toxicity data using USF procedure B 200–800 °C rising temperature, 40 °C min⁻¹, no forced air flow^a

| Material | Time to death (min) | Time to incapacitation (min) | No. of tests | No. of animals |
|--|---------------------|------------------------------|--------------|----------------|
| Polyvinyl chloride, 1 | 16.84±0.93 | 12.69±2.84 | 2 | 8 |
| Phenolphthalein polycarbonate | 16.92±0.13 | 14.15 | 1 | 4 |
| Rayon fabric, 100% | 17.00±7.13 | 8.59±0.24 | 2 | 8 |
| Polyurethane flexible foam, FR, 1.50 pcf, C2 | 17.12±1.72 | 12.37±2.26 | 2 | 8 |
| Asphalt coated organic roof felt | 17.20±1.23 | 13.93 | 1 | 4 |
| Nylon fabric, brushed | 17.22±4.08 | 13.24±2.81 | 2 | 8 |
| Polyurethane rigid foam, FR, 18.5 pcf | 17.29±0.96 | 12.12±0.16 | 2 | 8 |
| Polychloroprene, 1 | 17.36±2.34 | 13.45±1.30 | 2 | 8 |
| Asphalt impregnated fiberboard sheathing | 17.44±2.05 | 10.99±3.61 | 4 | 16 |
| Polyurethane flexible foam, FR, 1.20 pcf, A2 | 17.48±0.64 | 12.50±1.31 | 2 | 8 |
| Vinyl, expanded, fabric, FR | 17.49±1.07 | 7.62±2.38 | 2 | 8 |
| Rayon fabric, 100% | 17.60±3.68 | 10.53±0.16 | 2 | 8 |
| ABS, 2 | 17.62±4.77 | 13.52±3.46 | 5 | 20 |
| Olefin fabric, 100% | 17.74±5.56 | 10.52±0.15 | 2 | 8 |
| Rayon fabric, 100% | 17.88±3.25 | 10.33±5.85 | 2 | 8 |
| Medium density hardboard | 17.87±3.42 | 9.69±0.95 | 4 | 16 |
| Cotton/rayon/acetate 58/38/4 fabric | 17.91±9.81 | 10.09±2.31 | 2 | 8 |
| Polyurethane flexible foam, 1.20 pcf, A1 | 18.21±1.57 | 12.78±0.45 | 2 | 8 |
| Chipboard | 18.23±0.95 | 9.68±1.08 | 4 | 16 |
| Polyurethane flexible foam, 1.50 pcf, C1 | 18.28±0.91 | 11.12±1.79 | 2 | 8 |
| FR cotton/FR rayon 50/50 fabric | 18.36±1.57 | 10.63±1.50 | 3 | 12 |
| Nylon fabric, 100% | 18.52±5.62 | 15.51±5.67 | 2 | 8 |
| Polyurethane flexible foam, FR, 1.45 pcf, B2 | 18.56±1.26 | 11.14±4.00 | 2 | 8 |
| Rayon fabric, 100% | 18.61±3.80 | 9.22±0.23 | 2 | 8 |
| Polyphenylene sulfide, 4 | 18.79±1.05 | 15.47 | 1 | 4 |
| Phenolic fabric, 100% | 18.81±4.84 | 12.92±3.22 | 4 | 16 |
| Nylon fabric, 100% | 19.10±3.34 | 13.34±1.89 | 2 | 8 |
| ABS, 1 | 19.30±4.25 | 11.35±1.32 | 2 | 8 |
| Chlorosulfonated polyethylene, 2 | 19.42±3.04 | 8.22±1.58 | 3 | 12 |
| Rayon/cotton/nylon 70/28/2 fabric | 19.43±2.61 | 11.14±7.58 | 2 | 8 |
| Olefin fabric, 100% | 19.49±0.81 | 8.26±1.05 | 2 | 8 |
| Coal tar saturated organic felt, 15 lb | 19.84±1.82 | 14.40 | 1 | 4 |
| Polyethylene, 2 | 19.84±0.29 | 8.86±0.80 | 2 | 8 |
| Rayon/acetate/cotton 43/35/22 fabric | 19.87±1.16 | 8.90±0.82 | 2 | 8 |
| Fiberboard soundstop | 19.88±5.04 | 13.00±1.13 | 4 | 16 |
| Polyphenylene oxide, modified | 19.96±3.61 | 8.65±2.29 | 2 | 8 |
| Rayon/nylon 72/28 fabric | 19.96±0.40 | 14.52±0.88 | 2 | 8 |
| Asphalt saturated asbestos felt, 15 lb | 19.99±3.01 | 14.77 | 1 | 4 |
| Dead level asphalt | 20.02±0.95 | 14.73 | 1 | 4 |
| Polystyrene, 1 | 20.03±2.97 | 15.18±0.76 | 2 | 8 |
| Polychloroprene, 3 | 20.13±1.09 | 15.70±0.92 | 2 | 8 |
| Polyurethane flexible foam, FR, 1.20 pcf, A3 | 20.13±1.06 | 13.58±2.00 | 2 | 8 |
| Polychloroprene flexible foam, 1 | 20.23±4.12 | 14.57±1.55 | 5 | 20 |
| Nitrile rubber, 1 | 20.24±1.09 | 13.84±1.74 | 3 | 12 |
| Polyvinyl fluoride | 20.50±2.05 | 16.94±2.39 | 2 | 8 |
| Fluorene polycarbonate | 20.52±1.96 | 16.77 | 1 | 4 |
| Cotton fabric, FR, 3 | 20.55±2.01 | 8.92±4.91 | 2 | 8 |
| Cellulose fiberboard, core board | 20.58±4.38 | 9.91±5.24 | 4 | 16 |
| Steep asphalt | 20.60±0.93 | 11.58 | 1 | 4 |
| Ethylene propylene diene terpolymer, 1 | 20.66±0.81 | 10.82±3.24 | 3 | 12 |
| Isocyanurate foam, urethane modified, glass fiber, 1 | 20.71±3.93 | 17.81±3.27 | 2 | 8 |
| Ethylene propylene diene terpolymer, 2 | 20.71±0.98 | 15.12±1.90 | 2 | 8 |
| Acrylonitrile rubber, 3 | 21.29±2.52 | 14.03±0.96 | 3 | 12 |
| Rayon/phenolic 50/50 fabric | 21.43±6.18 | 15.39±1.95 | 3 | 12 |
| Chlorinated polyvinyl chloride, 1 | 21.76±4.22 | 6.29±0.60 | 3 | 12 |
| Bisphenol A polycarbonate, FDA grade, reference | 21.87±2.28 | 16.77±1.66 | 34 | 136 |
| Polyisoprene, natural rubber | 22.13±1.73 | 15.35±4.32 | 3 | 12 |
| Chlorosulfonated polyethylene, 1 | 22.35±3.44 | 17.06±2.61 | 4 | 16 |
| Pitch asphalt | 22.41±0.30 | 17.67 | 1 | 4 |
| Polyethylene, 3 | 22.60±0.62 | 16.68±2.23 | 2 | 8 |
| Isocyanurate foam, urethane modified, glass fiber, 2 | 22.66±3.27 | 20.00±4.31 | 2 | 8 |
| Chlorinated polyvinyl chloride, 2 | 22.74±6.22 | 9.00 | 1 | 4 |
| Nylon fabric, 100%, treated | 22.74±2.62 | 10.49±3.14 | 4 | 6 |
| Bisphenol A polycarbonate, 1 | 23.04±5.25 | 16.02±1.86 | 2 | 8 |
| Polychloroprene, 4 | 23.16±2.04 | 10.95±5.21 | 3 | 12 |

Table 1. Relative toxicity data using USF procedure B 200-800 °C rising temperature, 40 °C min⁻¹, no forced air flow^a

| Material | Time to death (min) | Time to incapacitation (min) | No. of tests | No. of animals |
|---------------------------------------|---------------------|------------------------------|--------------|----------------|
| Polyurethane rigid foam, FR, Q2 | 23.52 ± 2.04 | 17.58 ± 4.59 | 3 | 12 |
| Nylon fabric, 100% | 23.75 ± 7.42 | 11.84 ± 2.35 | 2 | 8 |
| Styrene butadiene rubber (SBR) | 24.11 ± 2.08 | 15.73 ± 6.25 | 3 | 12 |
| Fiberglass/nylon fabric | 24.60 ± 4.50 | 14.82 ± 3.45 | 2 | 8 |
| Chlorinated polyethylene rubber, 1 | 24.80 ± 0.10 | 7.50 ± 1.10 | 2 | 8 |
| Polychloroprene flexible foam, 2 | 25.59 ± 3.81 | 12.52 ± 3.87 | 6 | 24 |
| Polystyrene, 2 | 26.16 ± 0.12 | 19.04 ± 0.39 | 2 | 8 |
| Chlorinated polyethylene rubber, 2 | 27.35 ± 4.21 | 11.11 ± 6.21 | 2 | 8 |
| Polychloroprene, 2 | 27.53 ± 4.71 | 14.48 ± 8.76 | 3 | 12 |
| High temperature insulation, perlited | n.d. | n.i. | 1 | 4 |
| Quartz | n.d. | n.i. | 4 | 16 |

^a Values given are mean ± standard deviation.Table 2. Relative Toxicity of Plastics by Generic Type^a

| Polymer | No. of samples | Time, min. | | No. of tests |
|---------------------------------------|----------------|--------------|-------------------|--------------|
| | | To death | To incapacitation | |
| Polyether sulfone | 3 | 12.30 ± 2.08 | 11.25 ± 1.93 | 7 |
| Polyphenylene sulfide | 4 | 13.21 ± 3.80 | 11.53 ± 2.68 | 9 |
| Polyaryl sulfone | 2 | 13.48 ± 3.17 | 10.31 ± 0.42 | 5 |
| Wood | 12 | 14.03 ± 1.48 | 9.92 ± 1.09 | 33 |
| Polyurethane flexible foam | 29 | 14.15 ± 2.84 | 10.45 ± 1.36 | 81 |
| Polyamide (nylon) | 3 | 14.36 ± 1.71 | 12.35 ± 1.44 | 7 |
| Polyphenyl sulfone | 1 | 15.46 | 13.32 | 2 |
| Polyurethane rigid foam | 7 | 15.49 ± 4.06 | 11.77 ± 2.95 | 17 |
| Polymethyl methacrylate (PMMA) | 1 | 15.58 | 12.61 | 2 |
| Polyvinylidene fluoride | 1 | 15.86 | 6.50 | 2 |
| Cellulosic board | 8 | 16.57 ± 3.54 | 10.10 ± 1.35 | 28 |
| Polyvinyl chloride (PVC) | 2 | 16.60 ± 0.33 | 9.32 ± 4.77 | 4 |
| Acrylonitrile/butadiene/styrene (ABS) | 3 | 17.13 ± 2.45 | 11.82 ± 1.52 | 9 |
| Polyethylene, including foam | 5 | 17.31 ± 3.73 | 10.67 ± 3.65 | 11 |
| Acrylonitrile rubber (NBR) | 3 | 19.13 ± 2.89 | 12.46 ± 2.56 | 9 |
| Polyphenylene oxide, modified | 1 | 19.96 | 8.65 | 2 |
| Bisphenol A polycarbonate | 3 | 20.40 ± 3.77 | 14.71 ± 1.68 | 24 |
| Polyvinyl fluoride | 1 | 20.50 | 16.94 | 2 |
| Ethylene/propylene/diene (EPDM) | 2 | 20.69 ± 0.04 | 12.97 ± 3.04 | 5 |
| Chlorosulfonated polyethylene | 2 | 20.88 ± 2.07 | 12.64 ± 6.25 | 7 |
| Polyisocyanurate rigid foam | 2 | 21.68 ± 1.38 | 18.90 ± 1.55 | 4 |
| Polyisoprene (natural rubber) | 1 | 22.13 | 15.35 | 3 |
| Chlorinated polyvinyl chloride | 2 | 22.25 ± 0.69 | 7.64 ± 1.92 | 4 |
| Polychloroprene, including foam | 6 | 22.33 ± 3.80 | 13.61 ± 1.69 | 21 |
| Polystyrene | 2 | 23.10 ± 4.33 | 17.11 ± 2.73 | 4 |
| Styrene-butadiene rubber (SBR) | 1 | 24.11 | 15.73 | 3 |
| Chlorinated polyethylene | 2 | 26.08 ± 1.80 | 9.31 ± 2.55 | 4 |

^a USF test method, procedure B. Values given are mean ± standard deviation between samples.

FURTHER DEVELOPMENT OF AN
INSTRUMENTED ANIMAL SYSTEM FOR TOXIC
THREAT ASSESSMENT OF MATERIALS

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ABSTRACT

Two different instrumented animal systems have been presented in the past for toxic threat assessment of materials: (1) The AETS (Animal Exposure Test System) which utilizes an external electrode belt system to record ECG (electrocardiogram) and respiration during experiments in the laboratory or in large-scale fire tests. (2) An instrumented T_i (Time to Incapacitation) rotating wheel which records the collapse of the animal when it can no longer continue to walk or run.

This paper describes the mating of these two systems into a single system so that the ECG/respiration data can be correlated with the T_i data to facilitate the selection of the more valuable endpoint, or, to use the two systems together to obtain more information than either alone can provide to the experimenter. The data from a series of experiments conducted with the combined system, using carbon monoxide exposure for comparison of the two methods, are presented.

INTRODUCTION

In a recent paper (1) two separate systems for monitoring animals (rats) were described. One system utilized the electrocardiogram/respiration (ECG/R) technique recorded from an external electrode belt hardwired to a connector in the top of the exposure chamber, then to signal conditioner and recorder (cassette tape and/or strip chart). The second system used the T_i (Time to Incapacitation) as an endpoint similar to the method of Spurgeon (FAA) but with a different sensing system. The question has been raised as to how well the different endpoints used in the two systems would correlate with each other. This paper describes a combined system in which both the ECG provides cardiac data directly from the rat and the T_i system gives an indication as to the collapse of the rat. Following collapse, a special a.c. circuit of the T_i sensing system is used to obtain respiration to determine respiratory arrest and the T_d (Time to Death).

BACKGROUND

The ECG/R monitoring system was developed under a contract with the NASA Ames Research Center (2). The T_i system was developed on Douglas funds specifically for use in a contract with the FAA to develop the Combined Hazard Index. The PARTS (Portable Animal Recording Test System) (3) was developed by Douglas to provide ECG/R recording with complete mobility and participation in fire tests at any location. In combination with a Douglas-developed multiplexer, one to six rats can be monitored for ECG/R in the same test. This unit is described in a 1977 report (4).

THE COMBINED SYSTEM

The major obstacle in combining the ECG/belt and umbilical with the T_i exposure chamber (Figure 1) was the presence of the central shaft which supported the two separate halves of the rotating cage. If the umbilical were to be brought into the chamber through the top and dropped through the slot to the rat, the umbilical would become wrapped around the shaft and result in a very poor or loss of the recording for ECG/R. This problem was solved by using a second drive motor on the other side of the chamber and eliminating the shaft between the two halves of the rotating cage (Figure 2) making each half completely independent of the other. Each shaft from the gear motor terminates at its respective half-cage, is one-quarter inch in diameter and is fixed in two places--by the coupling on the gear motor and by the bearing surface on the joint of the two halves of the plexiglas chamber. The cage halves are affixed to the quarter inch shaft by a square, shortened shaft welded to a square plate which is bolted to the cage half. Each gear motor is controlled by a variable speed controller which is also capable of reversing the wheel direction if desired when the rat turns around within the cage. The rpm speeds of the two halves of the cage are synchronized by setting one controller to the desired rpm and visually adjusting the speed of the other to be synchronous. This takes very little time and slight differences in rpm seem

to make no difference to the rat. The upper and lower sections of the chamber are firmly clamped together with a silicone rubber gasket seal to reduce the leakage from the chamber.

The belt umbilical extends upward through the split cage to a modified Swagelok tubing fitting in the top of the chamber. The fitting was drilled out to permit a miniature female wire connector to slip through it and mate with the male half of the connector and wire cable leading to the signal conditioner in the PARTS and a two-channel Gould Brush recorder.

METHODS

At the present time the combined system has been used only with carbon monoxide (CO) at or near two concentrations: 0.8% and 1.4%. Figure 2 shows the schematic of experimental setup. Oxygen and CO in the exposure chamber were recorded using a Teledyne oxygen meter and an MSA LIRA CO meter Model 303, respectively. Carbon dioxide concentrations building up in the chamber were also recorded using a Beckman Model 864 NIR meter (not shown). Data generated by each of the gas meters was read once per second and recorded in memory on a Hewlett Packard Data Acquisition System (3052A). At the end of the test run, the concentrations curves for CO, CO₂, and O₂ in the chamber were plotted. The ECG was recorded on one channel of the Gould recorder and the contact bar output (T_i) on the other. When the subject reached T_i, the rotation was stopped and that channel was switched to the more sensitive a.c. circuit to monitor respiration to determine T_d. The ECG was recorded on the cassette tape in the PARTS as well as on the strip chart recorder. Figures 3 and 4 are typical recordings from two tests.

After placing the rat (Sprague-Dawley) in the wheel and sealing the joint, the cage was started rotating and synchronized at 4 rpm. In a few minutes, when the subject adjusted to the rotation, CO was injected into the chamber. Fifty milliliters (ml) provided a concentration of 0.8% and 90 ml provided an approximate concentration of 1.4%. These injection volumes were pre-calculated by computer. The chamber atmosphere was circulated through the analyzers and back into the chamber at a rate of 1 liter/min using a teflon diaphragm pump. One minute was required to mix the gases and achieve equilibrium. The free volume of the chamber containing the rat and wheel was 5.83 liters. The instrument loop added 500 ml making a total volume of 6.33 liters. Mixing factors included a deflector at the inlet port, the rotation of the wheel, animal movement, and the recirculation pump. Figure 5 shows a computer plot of the CO, CO₂, and O₂ in which 90 ml of CO which provides approximately a 1.4% concentration of CO.

RESULTS

The objective of these tests was to compare the time of occurrence of the C_a and the T_i so that one could be selected in preference to the other, or the decision made to use both in the combined system. Table 1 shows the

variations between the C_a and the T_i in eight tests at 1.4% CO. The variation is from 2 to 33 seconds, the average being 17.88 seconds. Figure 6 shows a linear least squares curve fit of the recorded C_a data against the recorded T_i data. The slope (0.9228) indicates that C_a occurs, on the average, about 8% sooner in time than does the T_i , with a correlation coefficient of 92.87%.

Figure 7 shows a computer plot of data recorded by the acquisition system for one test with the subject walking at 4 rpm. A 90 ml syringe volume of pure CO was injected to achieve a chamber concentration close to 1.4% (14,000 ppm), and which decreased gradually due to CO uptake by the subject. The CO₂ generated by the subject slowly increases during the test run. The oxygen depletion was minimal in each test, and made no significant contribution to the C_a or to the T_i .

The CO meter plots for most of the test runs, made by injections of 85-90 ml of pure CO, achieved concentrations of approximately 1.4% (range 1.2-.4%). The recorded T_i endpoints for eight tests at these concentrations were plotted individually in Figure 8. The curves shown were plotted from the predictive equation published by Crane et al. (Reference 5). The two curves relate T_i for rats of 200 grams and 350 grams body weight with constant CO levels in a test chamber exposure. The subject weight in grams is shown for each plotted T_i point. Although some scatter in results appears with respect to the prediction curves, the T_i points (with two exceptions) seem to show a general trend toward slightly longer T_i times than is predicted by the Crane data.

DISCUSSION

Practically speaking, the average variation of 17.88 seconds between the C_a and the T_i is of little significance in the testing of materials. In large-scale fire tests each of the methods has certain disadvantages which must be weighed one against the other for selection and use in a specific fire test. One disadvantage of the T_i rotating wheel is that when the T_i point is reached, the endpoint is not always clearcut so long as the wheel is rotating. Sometimes several rotations can occur after T_i and when the subject is not visible because of smoke or the nature of the test configuration, the exact endpoint can be missed by 30-60 seconds. After rotation has been stopped, the subject must be lying on the contact bar in an optimum position in order to obtain respirations for determination of T_d . The use of the a.c. circuit in the Douglas system, which increases the sensitivity of the respiratory signal 300x, makes it considerably easier to obtain respiration and determine T_d . This has been a very useful addition to the system.

The ECG method also has certain disadvantages: electrical interference can affect the recording, subject activity can also temporarily obscure the ECG, or the belt can slip and change the signal. These are infrequent occurrences, however, and can usually be avoided by careful application of the belt and checking the recording prior to the start of the test.

The T_i system has been used in a number of large-scale tests in the Douglas CFS (Cabin Fire Simulator) and in general has worked satisfactorily except for the point mentioned above. The ECG system has also been used in a greater number of large-scale tests and it is generally preferred by our investigators because more information can be obtained with this method. Figure 9 illustrates the kinds of data that can be obtained from the cardiogram alone. It is not necessary, however, that all this information be utilized in the evaluation of materials. The primary endpoint is the onset of a significant cardiac arrhythmia which indicates the fact that the subject is in serious trouble. It is not necessary to be a physician or a physiologist to interpret the onset of the arrhythmia. It is usually quite obvious and easily detected by any investigator once he has learned what to look for on the recording chart.

CONCLUSION

In the final analysis, it appears to make little difference whether the ECG or the T_i system is used because the two endpoints occur so close together, within the margin of error for either one. If possible it would be better to use the combined system because more information can be obtained from the use of the two together in the same unit, and where one might fail, the other may provide the necessary information.

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3. Reibold, R. C., "Portable Animal Recording Test System". McDonnell Douglas Corporation Report No. MDC J8551 (in preparation).
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5. Crane, C. R., Sanders, D. C., Endecott, B. R., Abbott, J. K. and Smith, P. W., "Inhalation Toxicology: I. Design of a Small Animal Test System; II. Determination of the Relative Toxic Hazards of 75 Aircraft Cabin Materials". Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, Oklahoma, FAA-AM-77-9, March 1977.

T_i EXPOSURE CHAMBER
(SIDE VIEW)

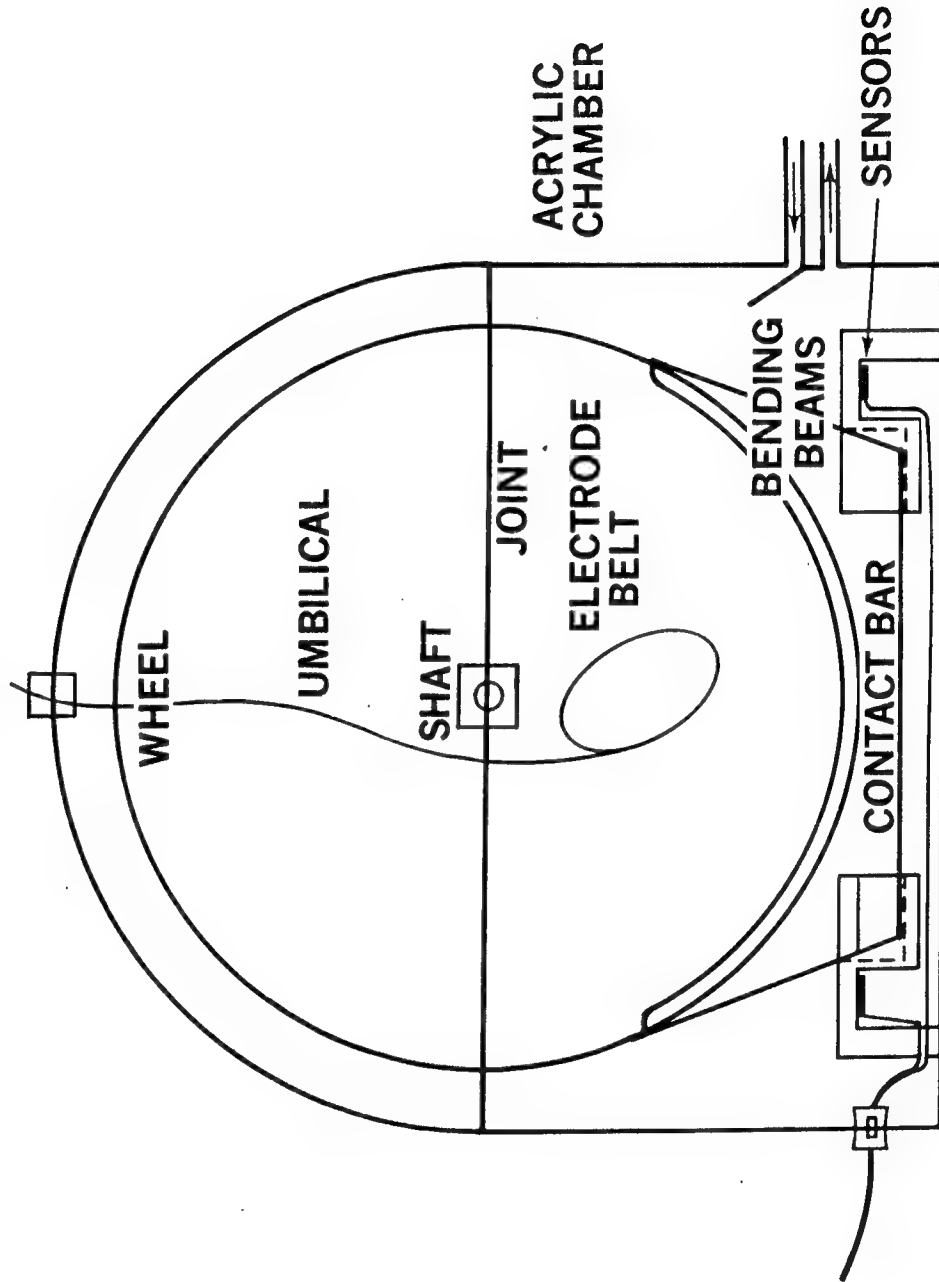
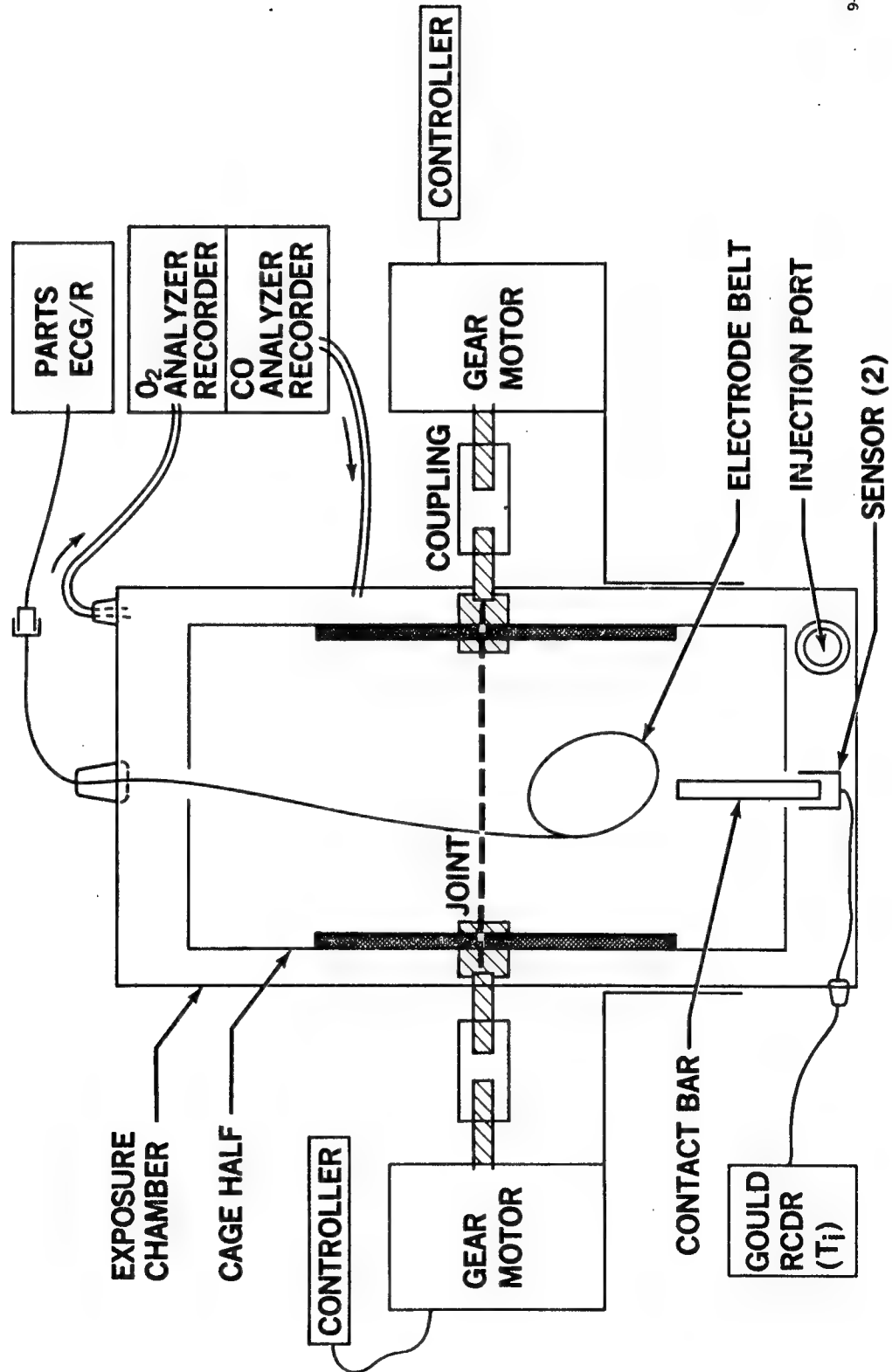


FIGURE 1

ECG/R/T_i EXPOSURE SYSTEM



9-DP-8269

FIGURE 2

TEST NO. 5 1.4%

PRETEST RECORD — ROTATION 4 RPM — CHART SPEED 5 MM/SEC

CHART DIRECTION →

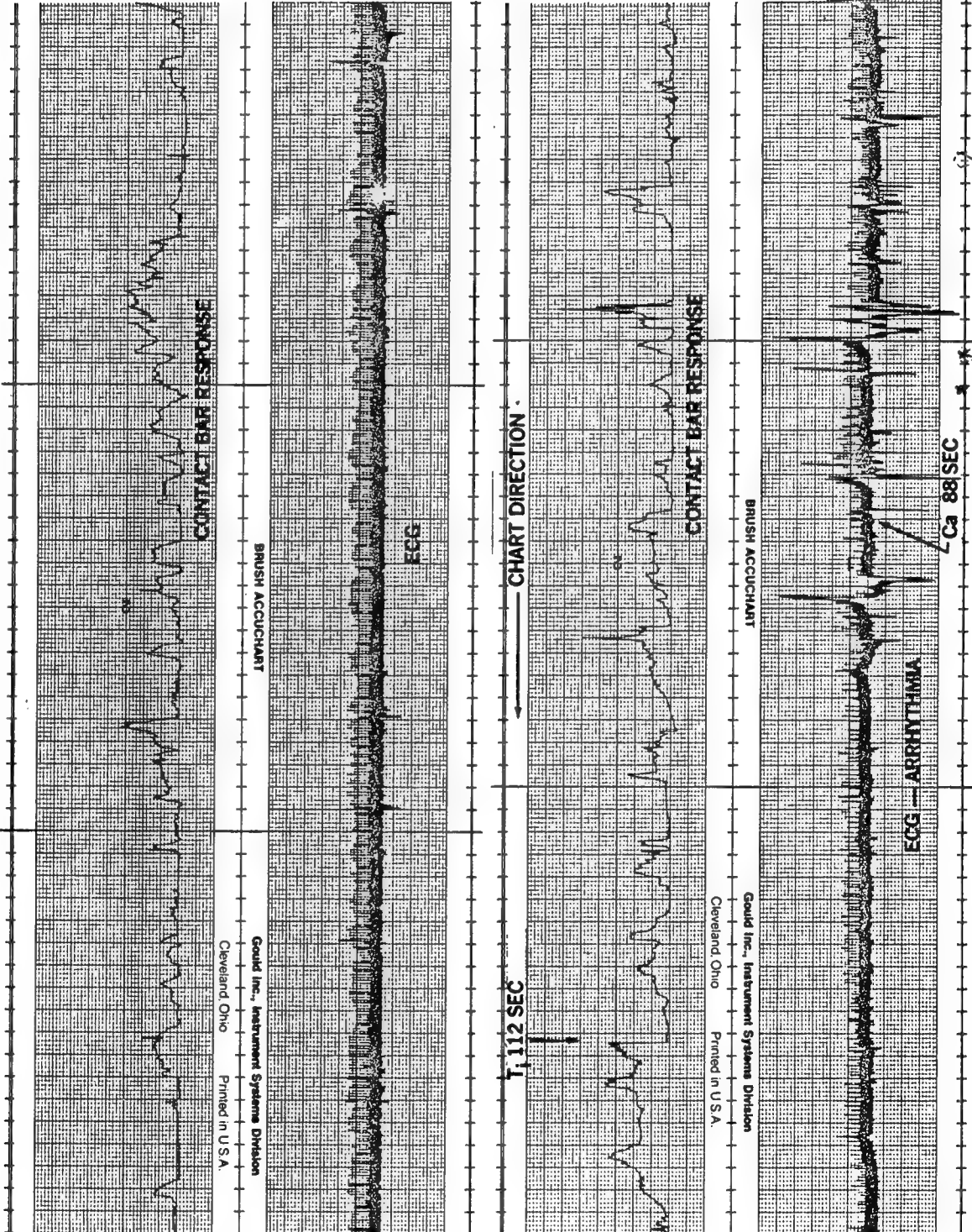


FIGURE 3

TEST NO. 9 1.4% CO

PRETEST RECORD — ROTATION 4 RPM — CHART SPEED 5 MM/SEC

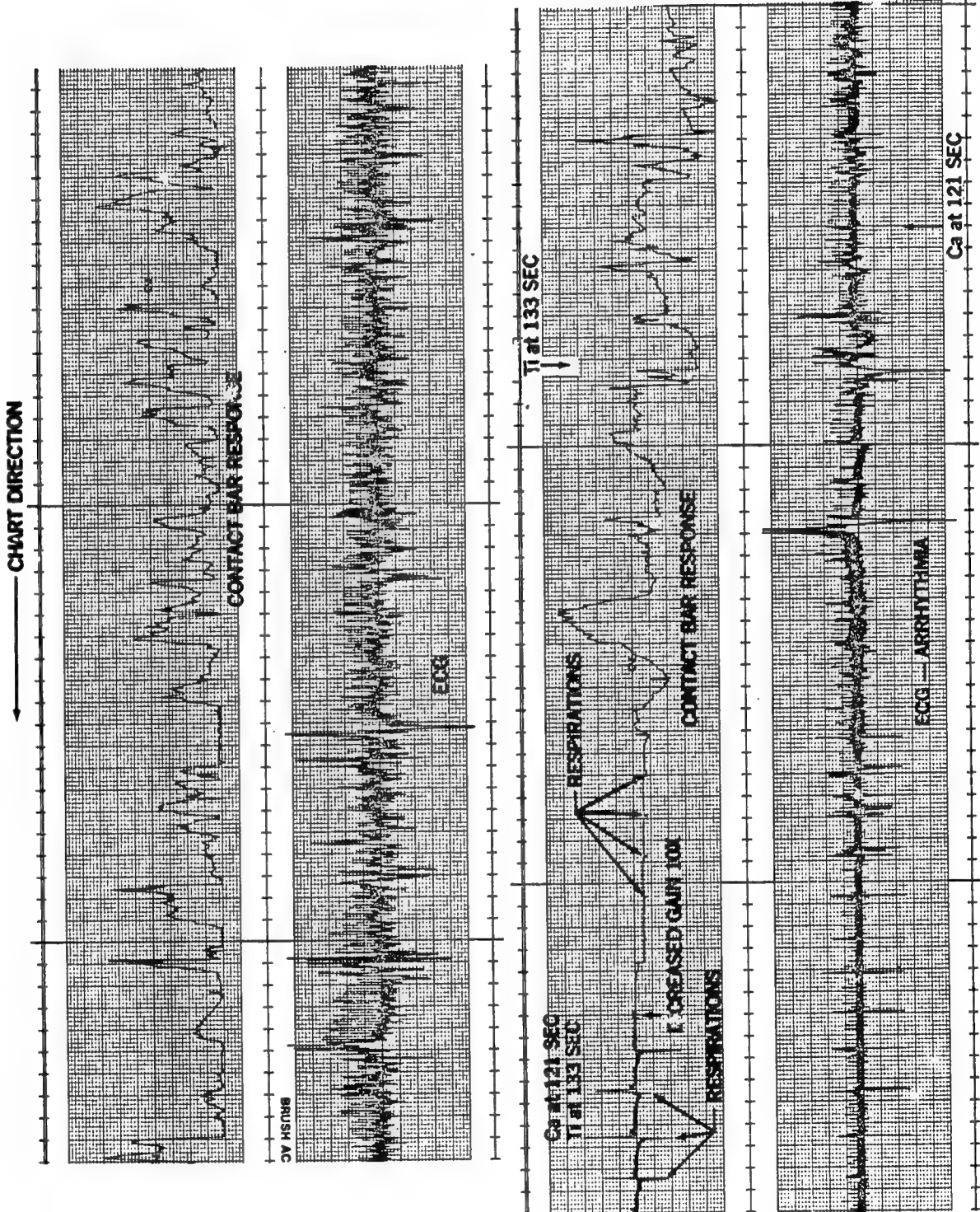


FIGURE 4

SATS CO₂, CO AND O₂ CONCENTRATION

CO₂ AND CO
CONCENTRATION
(1000 PPM)

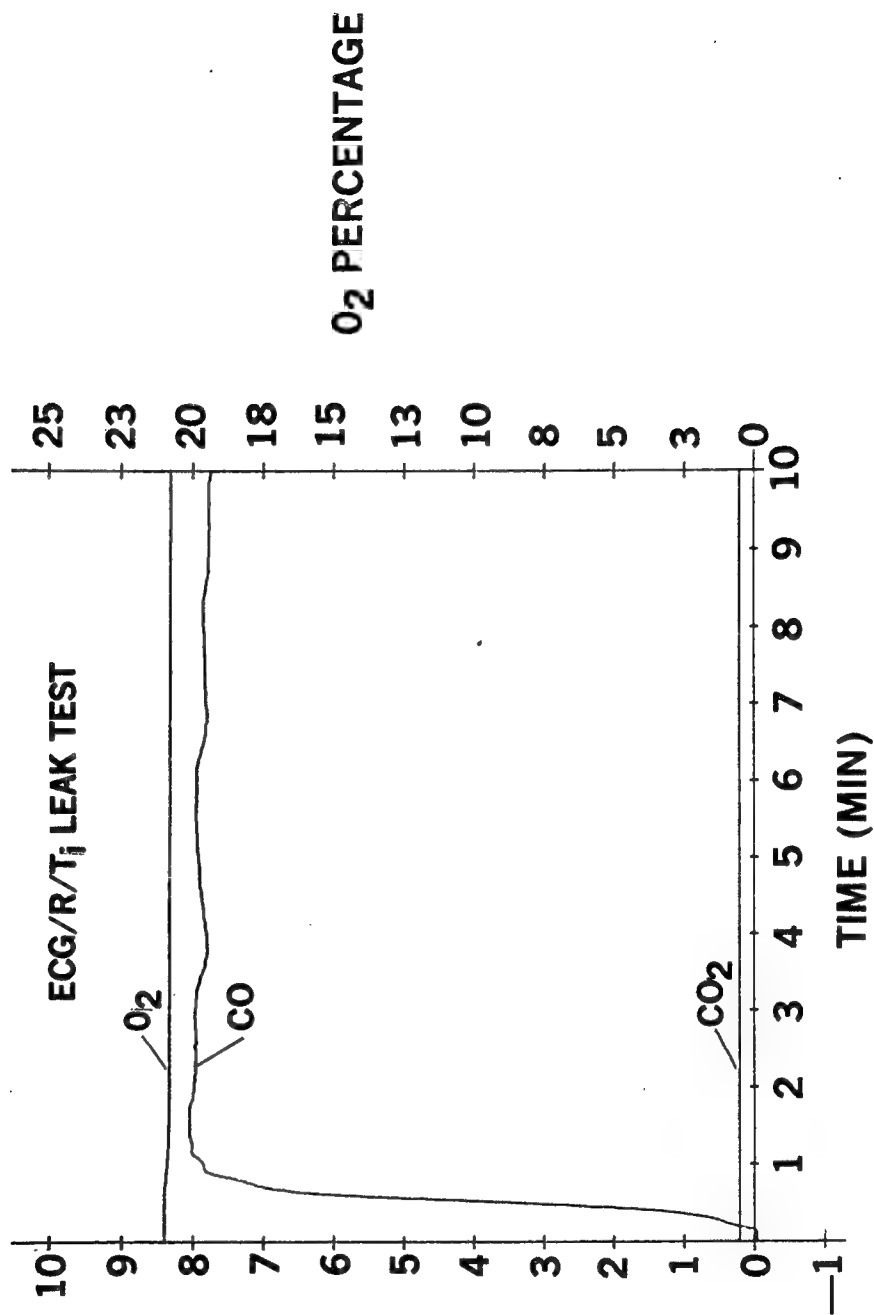


FIGURE 5

C_a VS T_i CORRELATION

(RATS EXPOSED TO 1.4% CO)

SLOPE = 0.9228

INTERCEPT = -6.3687

CORR COEF = 0.9287

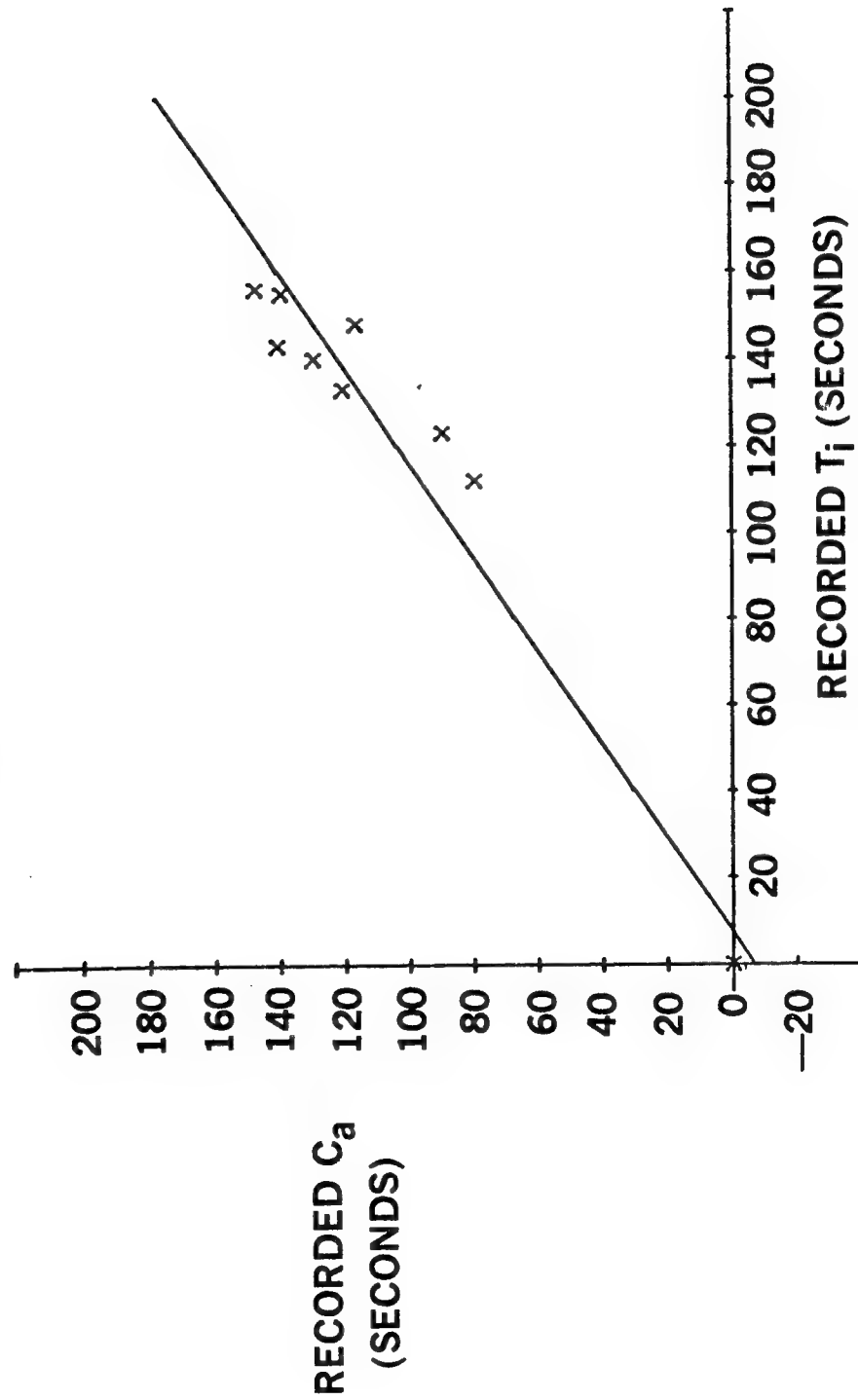
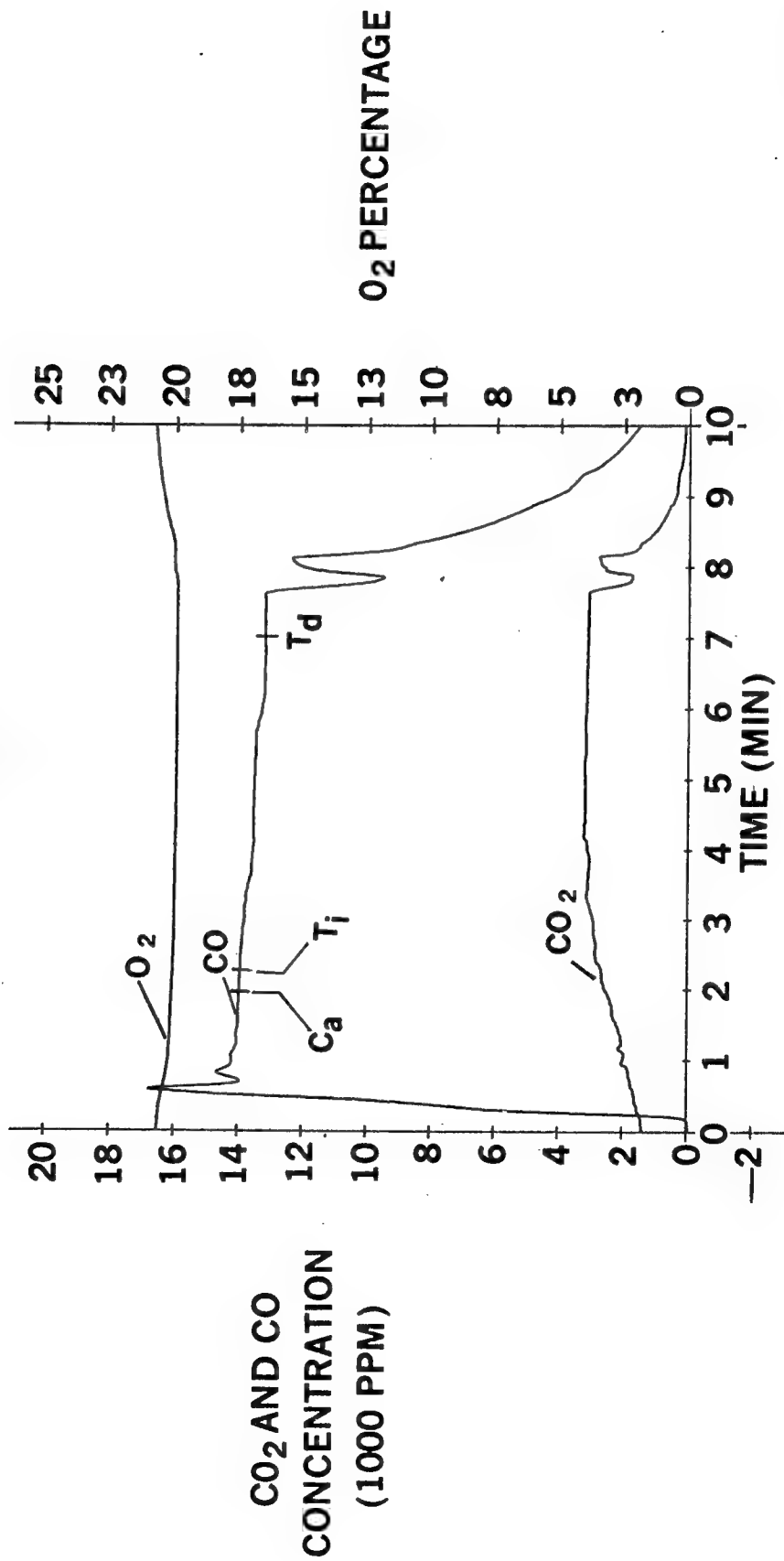


FIGURE 6

ECG/R/T_i CO₂, CO AND O₂ CONCENTRATION

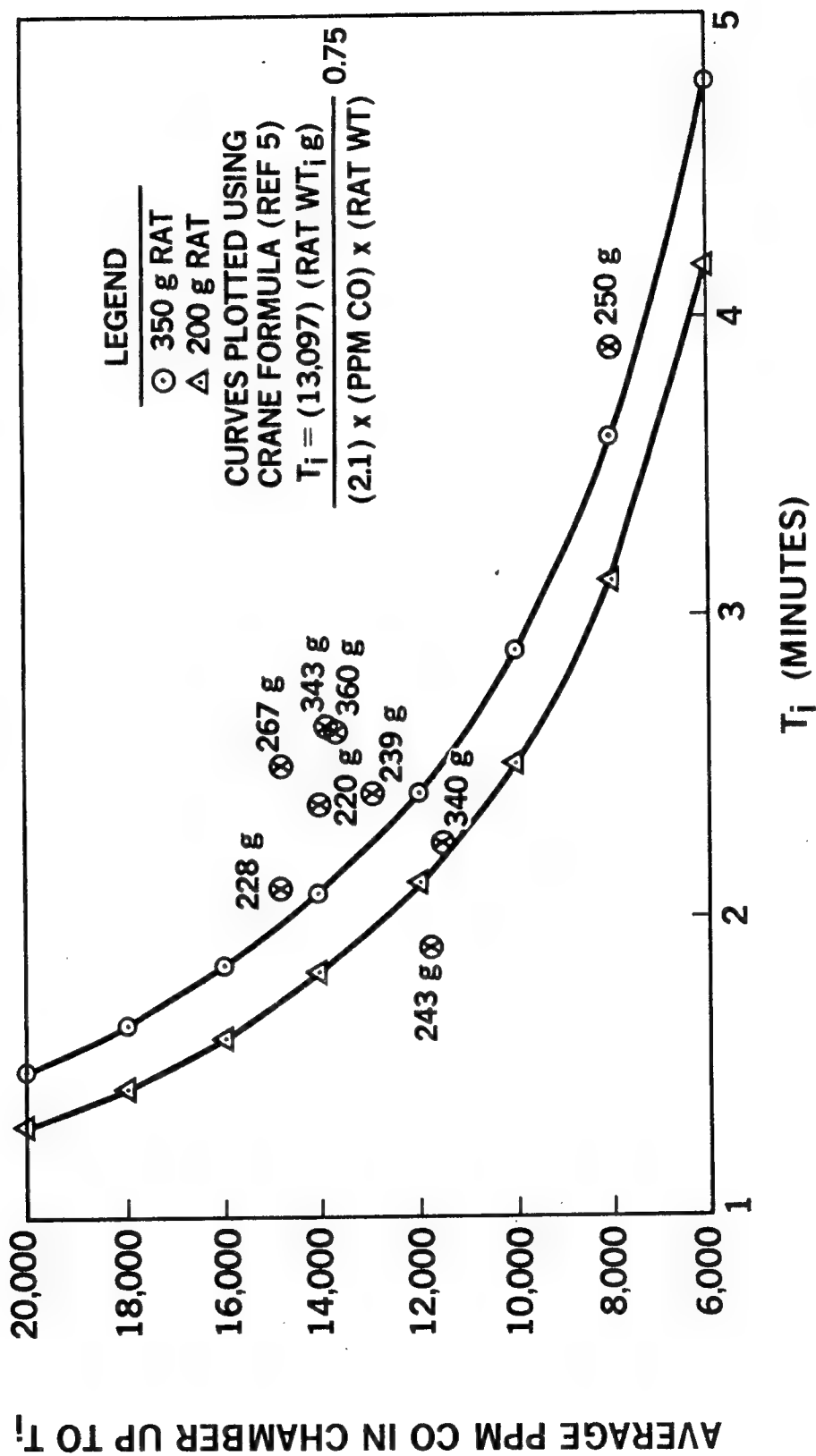
RUN NO. 7
RAT TEST



9-DP-8275

FIGURE 7

COMPARISON OF RECORDED T_i DATA WITH PREDICTED T_i USING CRANE FORMULA



9-DP-8274

FIGURE 8

TIME HISTORY OF PHYSIOLOGICAL EVENTS

374

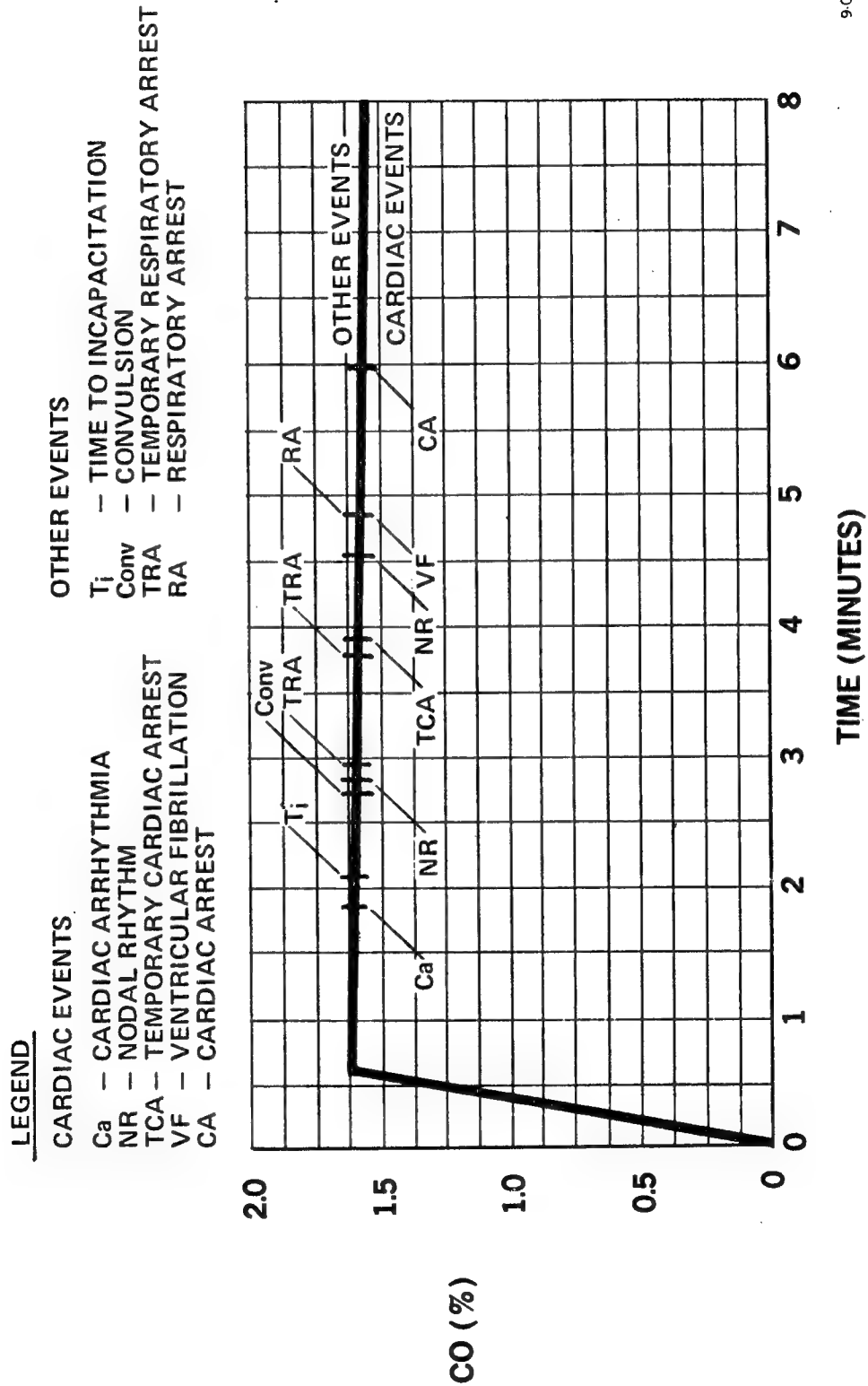


FIGURE 9

ECG/R/T_i TESTS

375

9-DP-8272

| TEST NO. | CO 1.4% | | Δt |
|----------|----------------------|----------------------|------------|
| | C _a (SEC) | T _i (SEC) | |
| 1 | 117 | 148 | 31 |
| 2 | 90 | 123 | 33 |
| 3 | 80 | 112 | 32 |
| 4 | 148 | 156 | 8 |
| 5 | 130 | 140 | 10 |
| 6 | 141 | 143 | 2 |
| 7 | 121 | 133 | 12 |
| 8 | 140 | 155 | 15 |
| | | | AVG 17.88 |

TABLE 1

SMOKE HAZARDS RESEARCH AT SRI INTERNATIONAL

A Progress Report

Stanley B. Martin, Director, Fire Research
SRI International

At previous conferences in this series--and most recently at the 1979 California Conference on Fire Toxicology--my colleagues and I have reported on what we believe to be a unique development in the technology of assessing hazards of smoke resulting from the exposure and involvement of materials in accidental fires. At the Fourth International Conference on Fire Safety, last January, the late Dr. James V. Dilley of our Toxicology Laboratory reported results of studies of acute lethality in rats. Today, I would like to update his presentation by reporting on research progress during the past year.

It's becoming increasingly apparent that:

- (1) Real progress toward a practical definition of smoke hazards,
- (2) Generally acceptable test methods for regulation of the fire-safe use of materials, and
- (3) Goal-directed development of safer materials

will have to await the basic research that is needed to provide a clear understanding of the issues. Premature attempts to date have yielded predictably poor returns. SRI's business is research, and we believe our contribution to the practical technology can best be made in the so-far-neglected basic research areas. Three of the basic issues we have addressed recently are:

- (1) Influence of burning conditions on the toxic potential of smoke.
- (2) Importance of thermal stability in the evaluation of smoke hazards.
- (3) Predictability of variations in smoke hazards from formulation differences within a particular polymer system.

A review of our results will constitute the major portion of my presentation here. **

* We use the term "smoke" in its broadest sense to include all airborne gases and vapors, as well as the visible aerosols, produced by thermally induced decomposition of materials, whether they result from combustion or pyrolysis without combustion.

** This is an abridged version of the original paper. The complete text is available on request. Write the author, SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025.

First, however, I would like to describe the experimental system--the apparatus and methodology. The development of this system at SRI has been a joint interdisciplinary effort involving physical scientists and engineers of our Fire Research Department, biomedical scientists and technicians skilled in hematology and pathology of our Toxicology Laboratory, and behavioral scientists of our Psychobiology and Physiology Department. I wish to acknowledge the important contributions made by all of these, especially Gordon Pryor, Deborah Palmer, Robert G. McKee, Jr., and the late James V. Dilley.

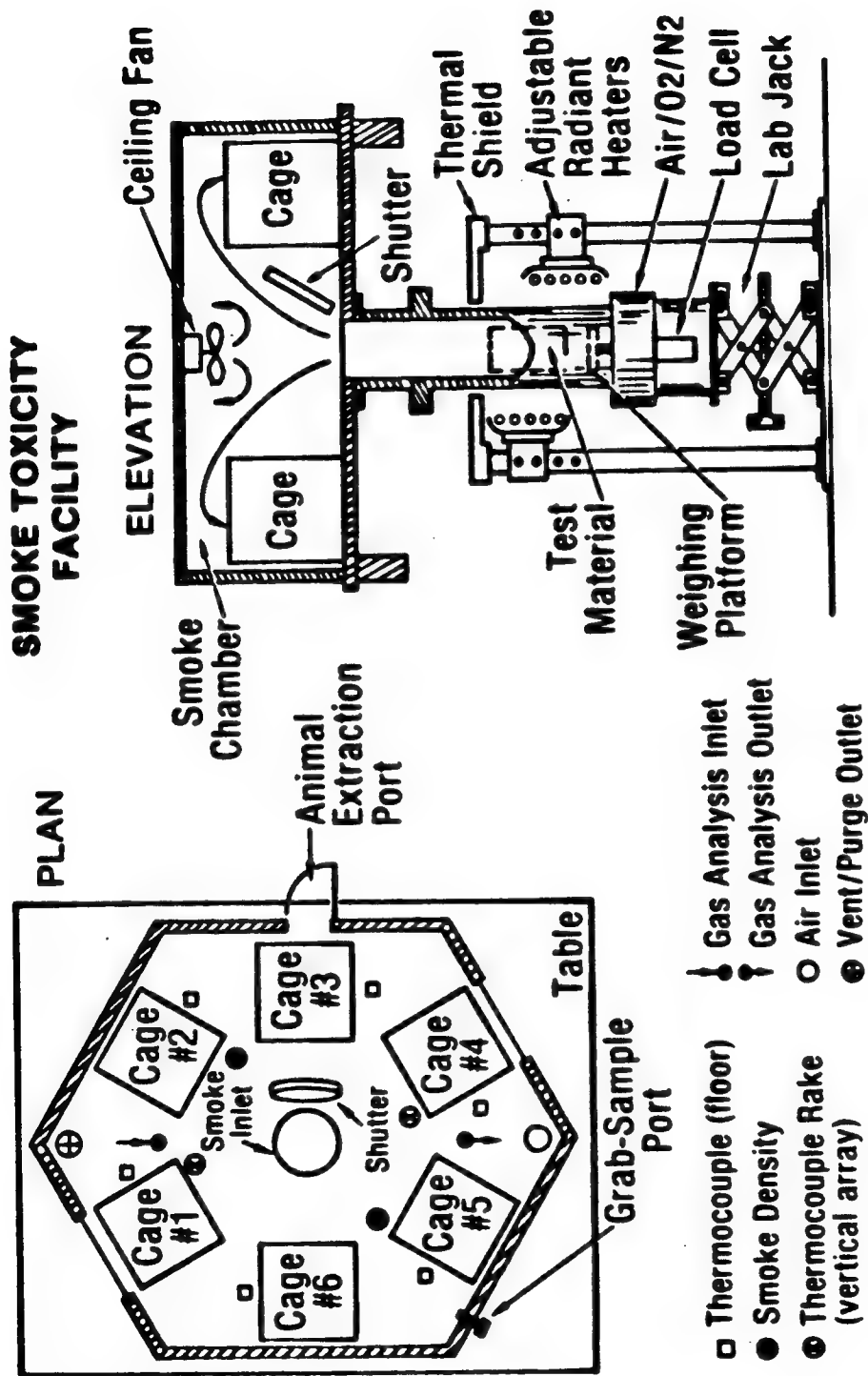
The development of the system was begun a few years ago (1977) in response to what we then considered to be a critical need in the area of smoke toxicology and for which there did not appear to be any adequate alternative systems at the time (Ref. 1). The system was designed to satisfy what we considered to be essential criteria for evaluating the relative smoke hazards associated with combustible materials. As it turned out, our criteria were sufficiently similar to the guidelines of the Committee on Fire Toxicology (Ref. 2) that the system and the methodology that we developed meet them as well.

Figure 1 shows a schematic diagram of the SRI system. The essential features of the system generally, and as they relate to the guidelines, are as follows:

- The animal exposure chamber, which is separated from the pyrolysis chamber and protected by a heat shield, has a large volume (1 m^3)-to-surface-area ratio.
- The test materials are pyrolyzed using adjustable high-intensity lamps and, therefore, a wide range of external radiant flux levels can be applied; flaming or nonflaming modes are available by controlling the sample atmosphere and providing a spark ignition system.
- The system is instrumented to provide continuous measurements of a variety of parameters needed to characterize the quality and quantity of the smoke generated and the conditions of the atmosphere surrounding the test animals.
- Six animals can be monitored simultaneously for determining the incapacitating effects of the smoke and ten or more can be exposed to determine lethality, to assess various physiological or chemical consequences of the exposure, or to determine sublethal organ or tissue pathology.

An important feature of the SRI system is its approach to fire-exposure simulation. Our basic premise has been that the composition of the smoke, and hence its toxic potential, while limited by the elemental composition of the material burning and in some degree dependent upon the material's polymeric structure, is not an intrinsic property of the material; rather it varies in some complex, unknown way with varying conditions of fire exposure, and cannot be defined without reference to those conditions. The dynamic character of fires, which involves many interacting and, at present, incompletely understood phenomena, makes the evaluation of fire-related extrinsic characteristics, such as smoke hazards, an extremely challenging endeavor, in no sense comparable to the measurement of an intrinsic property. At the very least, it demands that the hazardous

FIGURE 1



property be evaluated over a range of values of the component variables that describe the likely conditions of exposure and the resultant modes of combustion that are likely to be exhibited in pertinent end-use situations.

Our development reflects our preference to impose boundary conditions upon the material under evaluation that we can associate directly with fires of different kinds, in different stages of development, and to employ configurations that we can associate with the end use.

To demonstrate the potentially large effects of combustion mode on toxic potential, we conducted an in-house study of acute lethality in rats from exposure to the smoke from a single, well-defined polymeric system, polyoxymethylene. We chose this polymer because of its relatively simple elemental composition (only C, H, and O) and because it is known to pyrolyze, under anaerobic conditions, to produce high yields of its monomer, the strong sensory and pulmonary irritant, formaldehyde. It also burns cleanly in air to generate little or no soot and minor amounts of complex organics.

Animals (Fischer 344 rats) were exposed for 30 minutes to a static concentration of the smoke produced under 3 distinctly different sets of conditions: (1) aerobic pyrolysis (without combustion) under an imposed radiant heat flux of 2.8 watts/cm^2 , (2) flaming combustion accompanied by an externally applied flux of 2.8 watts/cm^2 , and (3) flaming combustion without externally applied flux (i.e., natural free (laminar) burning in a pool configuration). In all three cases the atmosphere was air.

In addition to lethality, hematological and gross pathological data were acquired to help explain the toxic effects of the smoke. Physical measurements included estimates of radiation fluxes to the polymer surface (including flame radiation); material weight loss; CO , CO_2 , and O_2 concentrations; and a crude measure of the formaldehyde produced. For the three modes of pyrolysis/combustion, values of the applied heat required to produce unit mass of smoke, L_v , were estimated from rates of weight loss used to calculate a Hazard Index (Ref. 3).

For each smoke-inhalation exposure, ten rats were housed, two per cage, in five open-mesh wire cages. These cages were uniformly distributed around the upper chamber of the apparatus as shown in Figure 1. The cage floors are raised to aid circulation of smoke. To facilitate retrieval from the chamber, rats for blood-gas analysis were placed in individual restrainers just above the chamber floor. All rats were observed and weighed prior to exposure. They were placed in the smoke inhalation chamber 5 minutes before exposure began.

Table 1 lists the estimated concentrations for 50 percent lethality resulting from half-hour exposures to the smokes from the three different pyrolysis/combustion modes. These concentrations are expressed in both the conventional units of mg/l (or the equivalent g/m^3) and in terms of the carbon monoxide present in the smoke. The two are related to one another through the mass yield of carbon monoxide.

As the data of Table 1 show, polyoxymethylene exhibited its greatest

Table 1

TOXIC END POINTS AND HAZARD INDEXES

| Parameter | Pyrolysis/Combustion Mode | | |
|--|---------------------------|--------------------|-----------------|
| | Pyrolysis Only | Flaming Combustion | |
| | | With Heating | Without Heating |
| LC ₅₀ · (mg/l) | 3.64 (3.16-4.22)* | 37.8(30.1 - ∞) | > 44.63 |
| LC ₅₀ (ppm CO) [†] | 119 (60-144) | 592 (432 - ∞) | > 240 |
| Hazard Index [‡] | 2.1 | 38.2 | > 27.7 |

*Numbers in parentheses indicate 95% confidence limits.

[†]Concentrations expressed in terms of CO content of smoke; for the same end point (i.e., acute LC₅₀ for ½-hour exposure), the concentration of CO alone--measured in the same apparatus--is 6100 ppm.

[‡]Hazard Index = (LC₅₀) · (L_v); units are cal/l or kcal/m³.

potential for toxic hazard when flaming combustion did not occur. In this case the blood-gas analysis showed HbCO levels always below 6.5% and, except for a slight acidosis, an otherwise normal blood-gas picture. The extreme toxic potential of the pyrolytic effluent with combustion absent is remarkable and suggests the presence of an unusually toxic component, which we assume to be formaldehyde. For half-hour exposure of rats to formaldehyde alone, Patty reports an LC₅₀ value of 830 ppm (Ref. 4). Our weight-loss-basis LC₅₀ for the combined components of the smoke from aerobic pyrolysis of polyoxymethylene (3.64 mg/l) requires a CH₂O yield of only 28% to account for the lethal endpoint by effects of formaldehyde alone, assuming Patty's value applies to smoke mixtures. Indeed, the surviving animals exhibited all the classic symptoms of formaldehyde intoxication during and after exposure, and at necropsy.

In contrast, the flaming combustion of polyoxymethylene portrayed a much less toxic picture in all observed and estimated parameters. Consistent with its high yield of carbon dioxide--indicating substantially complete combustion--the free-burning case exhibited few clear signs of toxic effects; the animals were relatively unaffected even when over half of the polyoxymethylene sample was consumed. The cases of flaming combustion driven by an external heat flux were intermediate, neither as toxic as the nonflaming case nor as innocuous as the free-burning case.

Such wide variations in the toxic responses of a single material, resulting from the mode of pyrolysis or combustion (and it should be remembered that our experiments were conducted only in normal, fully oxygenated air), clearly indicate that the hazards associated with possible fire involvement of any material product cannot be assessed in any meaningful way without subjecting the material

to test conditions that appropriately simulate the potential range of end uses and scenarios.

Now, I would like to describe our animal model for assessing the incapacitating effects of smoke--the NAS Committee on Fire Toxicology regards this aspect as the most important criterion--and show how the data generated from this model can be used to compare and rank materials as to the toxicities of the smokes they produce and their relative resistance to thermal decomposition. Details of the animal model and associated training regimen were previously reported (Ref. 5).

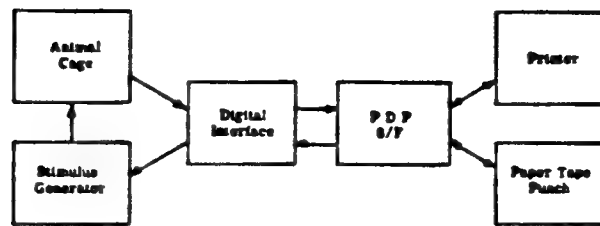
In selecting a suitable behavioral model for evaluating the incapacitating effects of smoke in the rat--which was our animal of choice and which conformed to the Committee guidelines-- we were guided mainly by the following consideration:

A person accidentally caught in an obvious smoke-contaminated environment, with or without the threat of heat or flames, is assumed to be highly motivated to terminate the exposure--either by extinguishing the source of the smoke or fumes or by removing himself or herself from the contaminated environment.

Therefore, the task used to monitor the incapacitating effects of the smoke in our rat model should incorporate as many of the elements required to simulate this situation as possible. That is, the task should involve high motivation on the part of the rat, and it should require the functional integrity of sensory systems, motor systems, and higher cognitive systems.

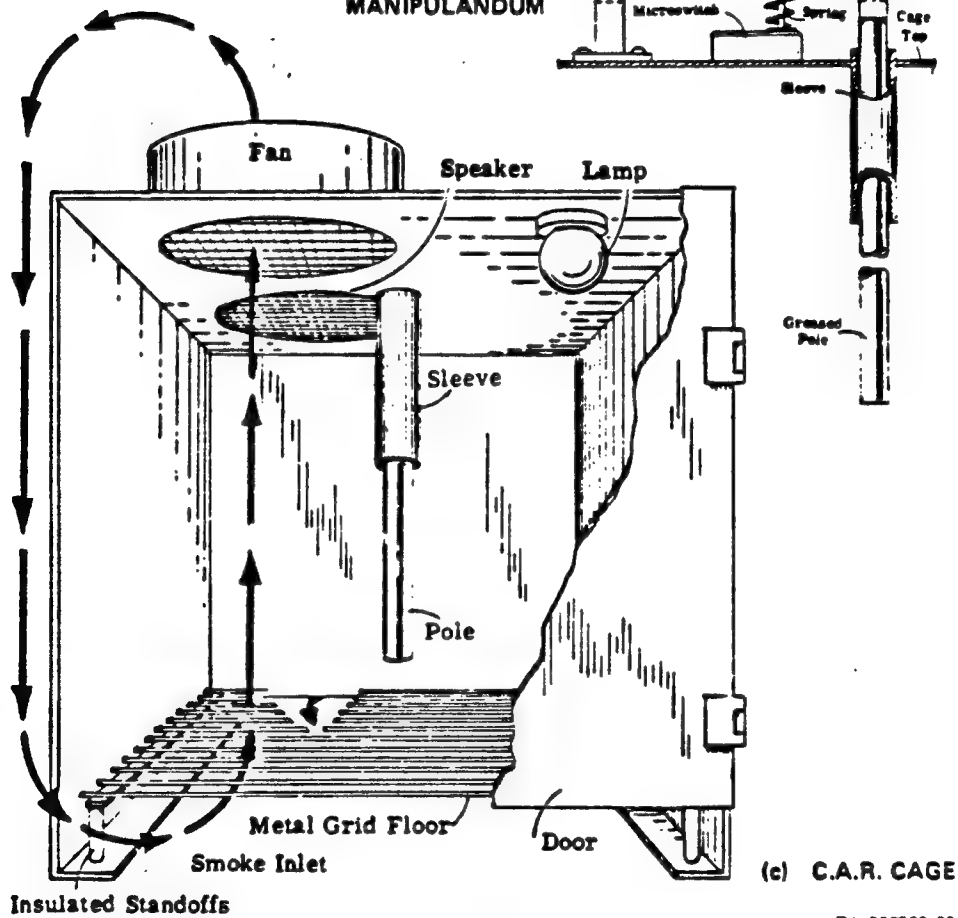
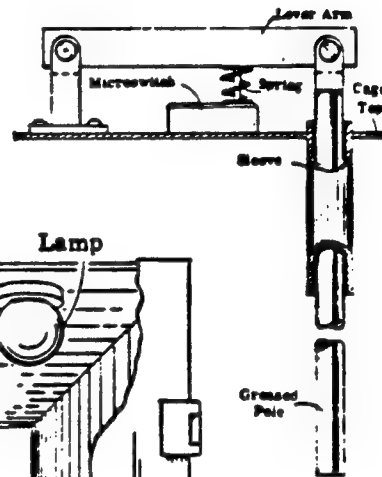
We chose aversive foot shock as a suitable motivator for the rat and performance of a conditioned pole-climb avoidance/escape response as a measure of sensorimotor function. We use stimuli in three sensory modalities--visual, auditory, and somesthetic--as the warning cues to signal the onset of the aversive foot shock. Thus, selective sensory and/or perceptual effects of the pyrolysis products can be revealed. Moreover, because the task is learned before exposure, any disruptive cognitive effects of the pyrolysis products might be evidenced by a nonspecific loss of the avoidance/escape response. Muscular coordination must be intact for the rat to be able to find and manipulate the pole effectively in order to avoid or terminate the aversive foot shock. Finally, the system is computer-automated for objective, reliable, and efficient operation.

Figure 2 illustrates the conditioned avoidance response (CAR) test chambers and associated equipment. The test chamber is constructed of stainless steel. Brass rods serve as the floor. The rods can be electrified with scrambled, constant-current shock of either aversive or nonaversive intensity. An aluminum pole is suspended from the center of the ceiling to provide the rat occupying the cage an escape from shocks. The pole is lubricated to discourage the rat from remaining on it. Downward displacement of the pole closes a microswitch that signals a response. A light bulb, a whisper fan, and a loudspeaker are also mounted in the ceiling. The light bulb provides ambient illumination. The fan provides circulation by drawing air and smoke from the open floor, through the chamber, and out the top. Six such chambers are positioned around the table above the smoke-generation system. A single hood encloses all the chambers. The test chambers are interfaced with a computer



(a) SYSTEM COMPONENTS AND INTERFACES

(b) ANIMAL RESPONSE MANIPULANDUM



(c) C.A.R. CAGE

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FIGURE 2 CONDITIONED AVOIDANCE RESPONSE APPARATUS

that provides automatic stimulus presentation and data collection. Data are recorded on a teletype and punched paper tape for offline processing.

The two principal measures examined are the percentage of rats that fail to avoid the painful foot shock by responding within the 10-second stimulus interval that precedes the foot shock (avoidance failures) and the percentage of rats that fail to respond throughout the trial including the 20-second interval of foot shock (escape failures). These measures are derived from the recorded times (in 0.1 second) to respond during each trial.

These parameters are analyzed as cumulative percentages over the entire 30-minute exposure interval and for each 5-minute interval during exposure and recovery.

Now, I would like to present some results to demonstrate how we can use the data generated by these methods to compare the relative toxicities of the smokes generated from three materials and to propose a method for comparing the relative hazards of these materials in a more general way that takes into account some aspects of their thermal stability.

Figure 3 shows the relative toxicities of the smokes from red oak, PMMA, and PPS expressed as the smoke concentrations (in g/m^3) found to cause a 50% increase in avoidance failures (CC_{50}), a 50% increase in escape failures (IC_{50}), and 50% mortality within two weeks (LC_{50}). Each value was estimated from the dose-response data. Of particular interest is the similarity between the incapacitating concentrations of smoke from red oak and PMMA compared with the relatively more potent smoke from PPS (which contains very little CO). Thus, based on these data, one would conclude that the smokes from red oak and PMMA were equipotent as behavioral intoxicants and that the smokes from both were much less toxic than that from PPS. Although this interpretation is essentially correct, it would be a mistake, in general, to also conclude that red oak and PMMA were necessarily safer materials than PPS in a fire situation because their thermal stabilities have not been taken into account. Thus, a material that produces extremely toxic smoke, but requires extreme amounts of heat to generate the smoke, may be relatively safer than one that produces less toxic smoke but is thermally unstable.

In order to begin to address this issue, we suggest that the following measure represents a first approximation to combining some of the physical characteristics of materials with the toxicities of the smokes that they produce. We suggest that a measure of the total applied heat required to produce an amount of smoke that causes some biological effect (including lethality) under specified conditions constitutes a meaningful way to compare materials as to potential hazard. The measure that we propose is the product of the incident heat flux (in $\text{cal/cm}^2/\text{sec}$) times the surface area of the material exposed (in cm^2) times the duration of heating (in seconds). This value, which we designate as total applied heat has units of calories. Two of the parameters--incident flux and time--can be measured with some accuracy, whereas the third--area exposed--is more problematical. Moreover, other parameters that may be as important or more so in a real fire situation (such as rate of fire spread) are not included. Nevertheless, we feel that this approach represents a first step toward a solution to the problem and that it offers an interim means of comparing materials that goes beyond simply comparing smoke toxicities. Also, we should caution that this method

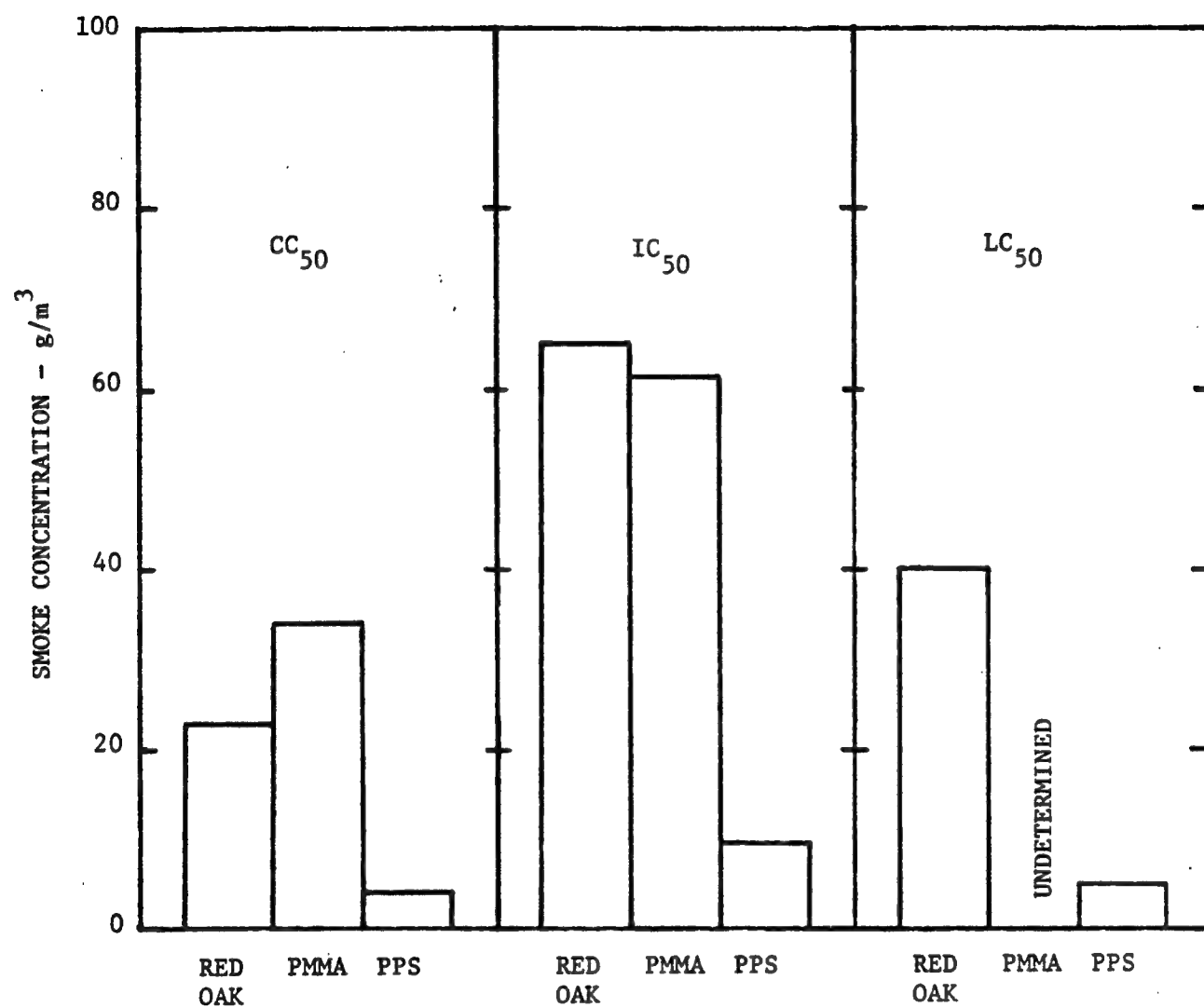


FIGURE 3 COMPARISON OF THE EFFECTS OF SMOKE FROM RED OAK, PMMA, AND PPS

was developed from data obtained using nonflaming conditions and that a somewhat different approach might be needed to deal with the flaming mode.

Figure 4 shows the application of this measure to compare the relative thermal stabilities of five materials pyrolyzed under essentially identical conditions. It clearly and dramatically points out the differences in thermal stability of the materials and emphasizes the need for taking this factor into account when comparing materials.

Figure 5 shows the results of applying this method to the data obtained from red oak, PMMA, and PPS. The biological endpoints are the same in this figure as they were in Figure 3. However, in this figure the independent measure is the total heat applied to the sample, whereas it was smoke concentration in the previous figure. In comparing the results in the two figures, note the shift in position of PMMA relative to red oak and PPS. Whereas PMMA was more comparable to red oak than PPS in terms of the toxicities of the smokes that they produced, it is more comparable to PPS in terms of the total heating required to produce that quantity of toxic smoke. Thus, we contend that PMMA and PPS are about equal in potential hazard as pyrolyzable materials in spite of the fact that PPS produces smoke that is about 6 times as toxic weight-for-weight in causing incapacitation.

As a final demonstration of the usefulness of this system, I would like to present the results of a series of experiments in which we compared the relative toxicities of the smokes and the thermal stabilities of a series of ten flexible polyurethane foams (Refs. 6,7). This work was done for a private sponsor, so that I cannot divulge (nor do I know) the exact compositions of the materials. However, I can say that they were all generically similar and that they all contained a fire retardant of one kind or another. The experiments were all carried out in the nonflaming mode in 4% oxygen-96% nitrogen atmospheres, and the applied heat flux was about $1.9 \text{ cal/cm}^2/\text{sec}$. The samples were exposed to the heat flux in a circular configuration.

Figure 6 shows the results in terms of the smoke concentrations required to cause 50% increase in avoidance failures as the measure of behavioral incapacitation (the smokes from these materials did not, in general, cause a sufficient number of escape failures to calculate an IC_{50} at the concentrations tested). The materials are listed and ranked in the figure according to their smoke toxicities from most to least toxic, material 1 producing the most toxic and material 10 producing the least toxic smokes in terms of behavioral incapacitation. The range is about 9.7 to 26.7 g/m^3 , or a factor of about 2.8 to 1.

Figure 7 shows the results in terms of the 2-week LC_{50} s. For these materials, deaths were typically delayed and occurred sporadically over the 2-week observation period. Clearly, in terms of the lethal toxicities of the smokes, this measure provides a different ranking of the materials than the measure of behavioral incapacitation. The range of LC_{50} s for the ten materials was 11.8 to 62.2 g/m^3 , or a factor of about 5.3 to 1. Materials 3 and 10 stand out as producing the least lethal smokes. It is interesting that these two materials contained the same fire retardant, which was different from the fire retardants in the other eight materials and was the only distinguishing feature.

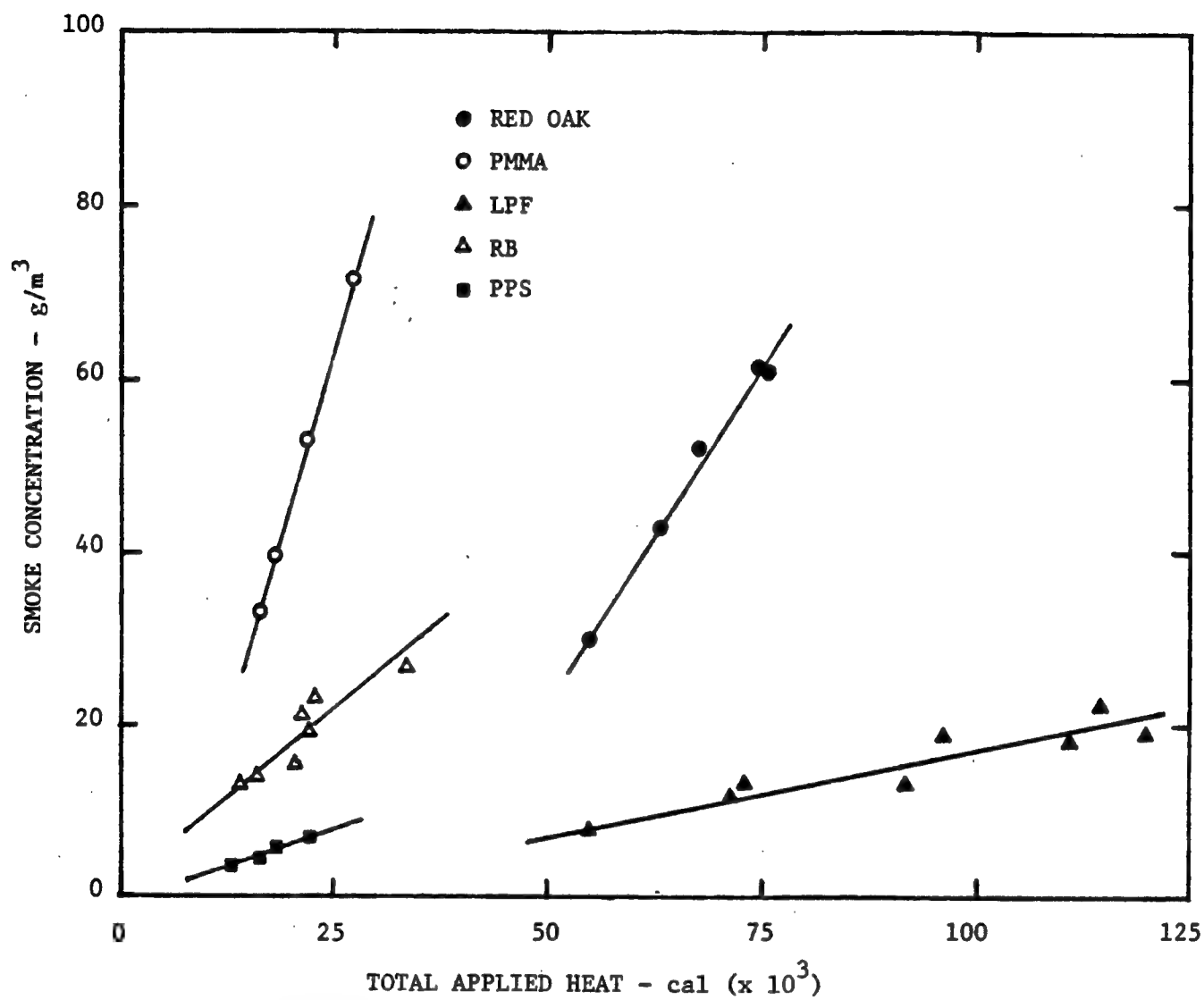


FIGURE 4 SMOKE CONCENTRATION AS A FUNCTION OF HEATING TO WHICH MATERIALS WERE EXPOSED

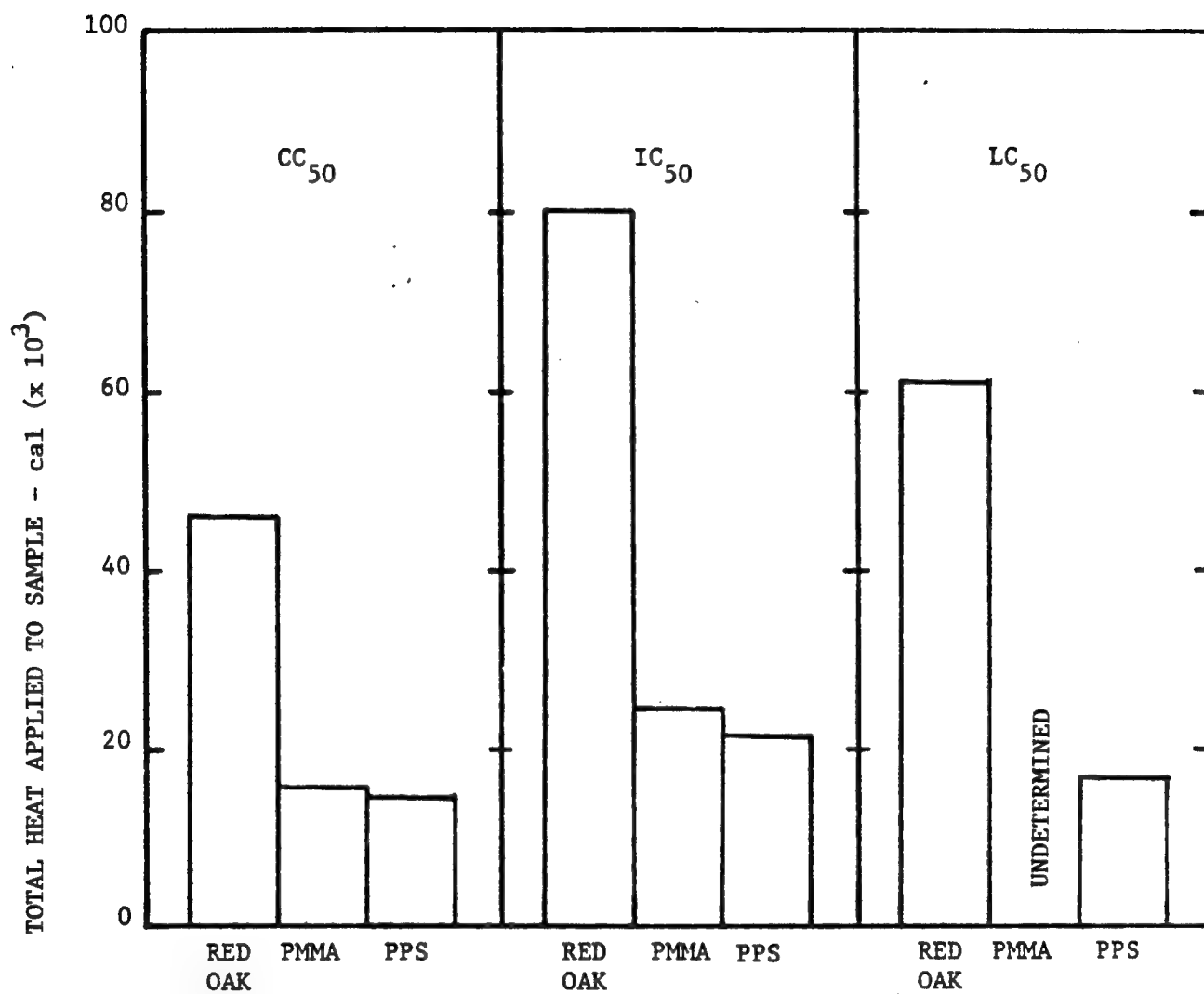


FIGURE 5 COMPARISON OF THE TOXIC HAZARDS OF RED OAK, PMMA, AND PPS

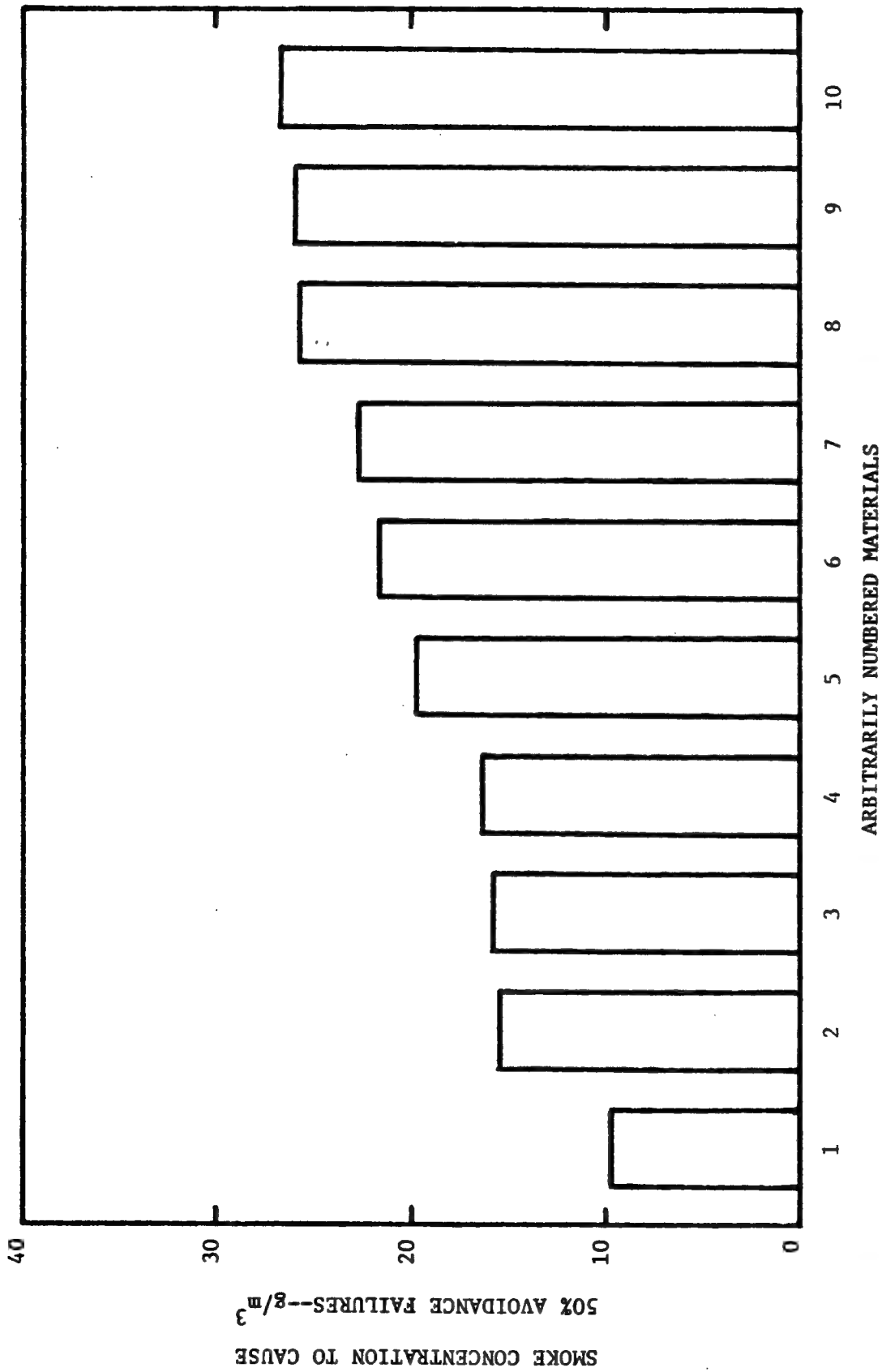


FIGURE 6 COMPARISON OF THE BEHAVIORAL TOXICITY OF SMOKE FROM TEN FLEXIBLE, FIRE RETARDED POLYURETHANE FOAMS, RANKED ACCORDING TO BEHAVIORAL INCAPACITATION

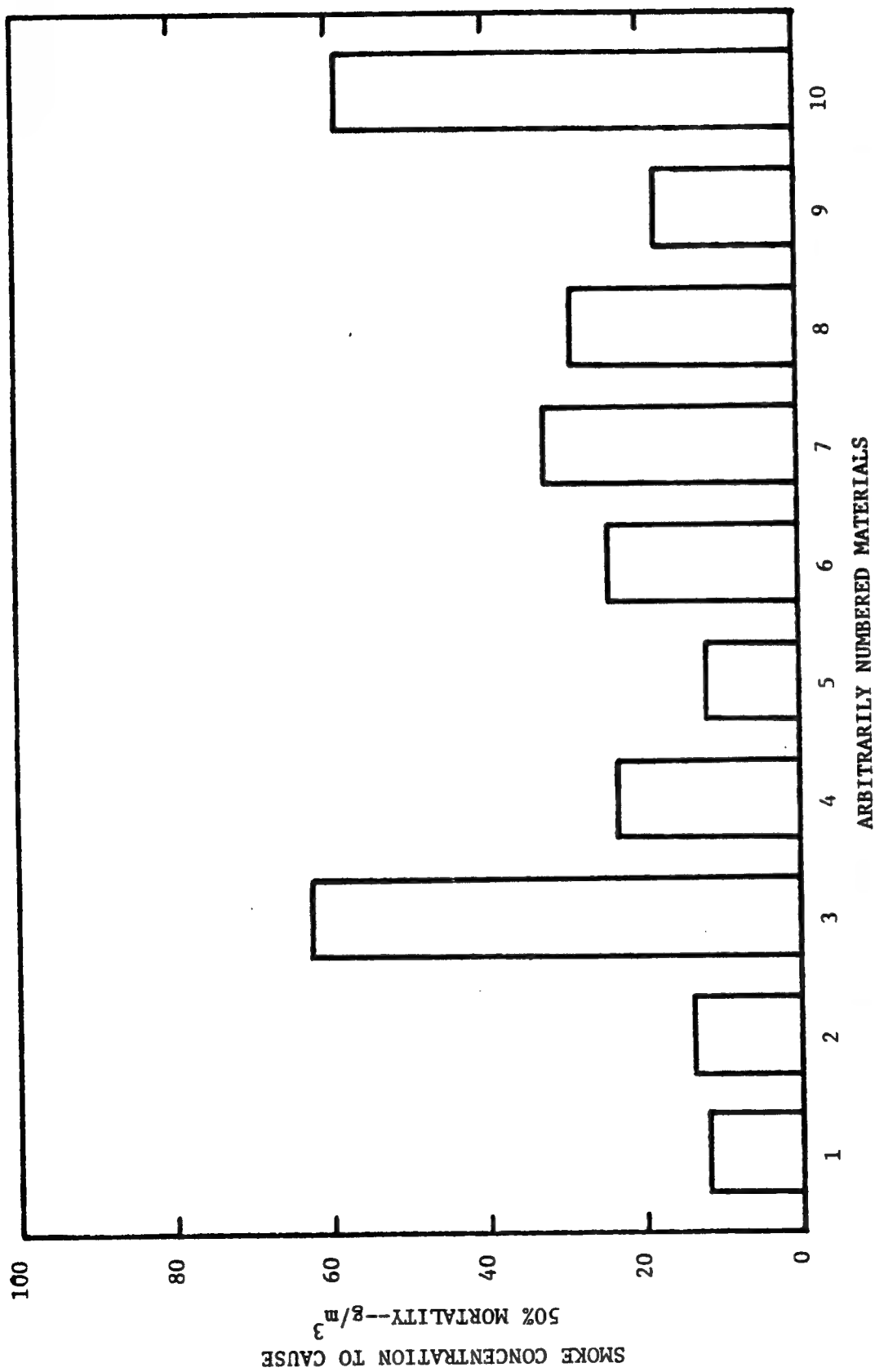


FIGURE 7 · COMPARISON OF THE LETHALITY OF SMOKE FROM TEN FLEXIBLE, FIRE RETARDED POLYURETHANE FOAMS LISTED ACCORDING TO RELATIVE BEHAVIORAL INCAPACITATION

Figure 8 shows a comparison of the ten materials in terms of the applied heat energy required to produce sufficient smoke to cause a 50% increase in avoidance failures. Using this measure a different ranking is obtained from that using the toxicities of the smoke per se. Thus, material 5, for example, which produced the fifth most toxic smoke was less stable thermally than some of the other materials and ranked second using this measure. This measure also increased the differences among materials, the range being 24.8 to 158.7 kcal, or a factor of about 6.4 to 1.

Figure 9 shows the 2-week LC_{50} s in terms of applied heat energy. As was the case with smoke concentration, the ranking of the materials changed appreciably when using lethality as the endpoint compared with behavioral incapacitation. Again, materials 3 and 10 stand out as being most thermally stable as well as producing the least toxic smokes. The range of LC_{50} s expressed in this way was from 22.3 to 364.6 kcal, or a factor of about 16.3 to 1.

Sometime after we had completed and documented our ranking of these ten polyurethane foams, we were provided with nondetailed generic information about their formulation and we were pleased to note systematic relationships between differences in formulation and our ranking of hazard. While there were included in the group one or more polyether-polyester hybrids, there was a roughly equal representation of the polyether class and the polyester class of polyurethanes. By our ranking, the polyethers were consistently among the more hazardous foams tested. Materials 3 and 10, the most thermally stable of the foams and the ones least likely to produce lethality, were the only members of the set having tetrakis (2 chloroethylene) diphosphate as their principal fire retardant moiety. We haven't attempted to evaluate the probability that these coincidences of apparent cause and effect could have occurred by chance, but we feel that they reflect actual (and possibly predictable) effects of formulation on smoke hazard. Clearly, the differences between behavioral effects and lethality are real.

In summary, we have found evidence pertaining to a few of the significant issues that need to be understood more fully before practical advances in smoke hazards technology can proceed. We have demonstrated for a simple polymeric system that there are strong (perhaps overriding would be a better word) effects of burning conditions on the toxic potential of smoke. We have shown conclusively the importance of considering the thermal stability of a polymeric system in evaluating any smoke hazards it may contribute to, and we suggest the inclusion of a factor such as the "heat of gasification" in any derived hazard index. Finally, we have shown retrospective evidence of effects on smoke hazards of formulation changes within a particular polymer system that may offer some optimism for eventual prediction of fire/smoke-safe formulations.

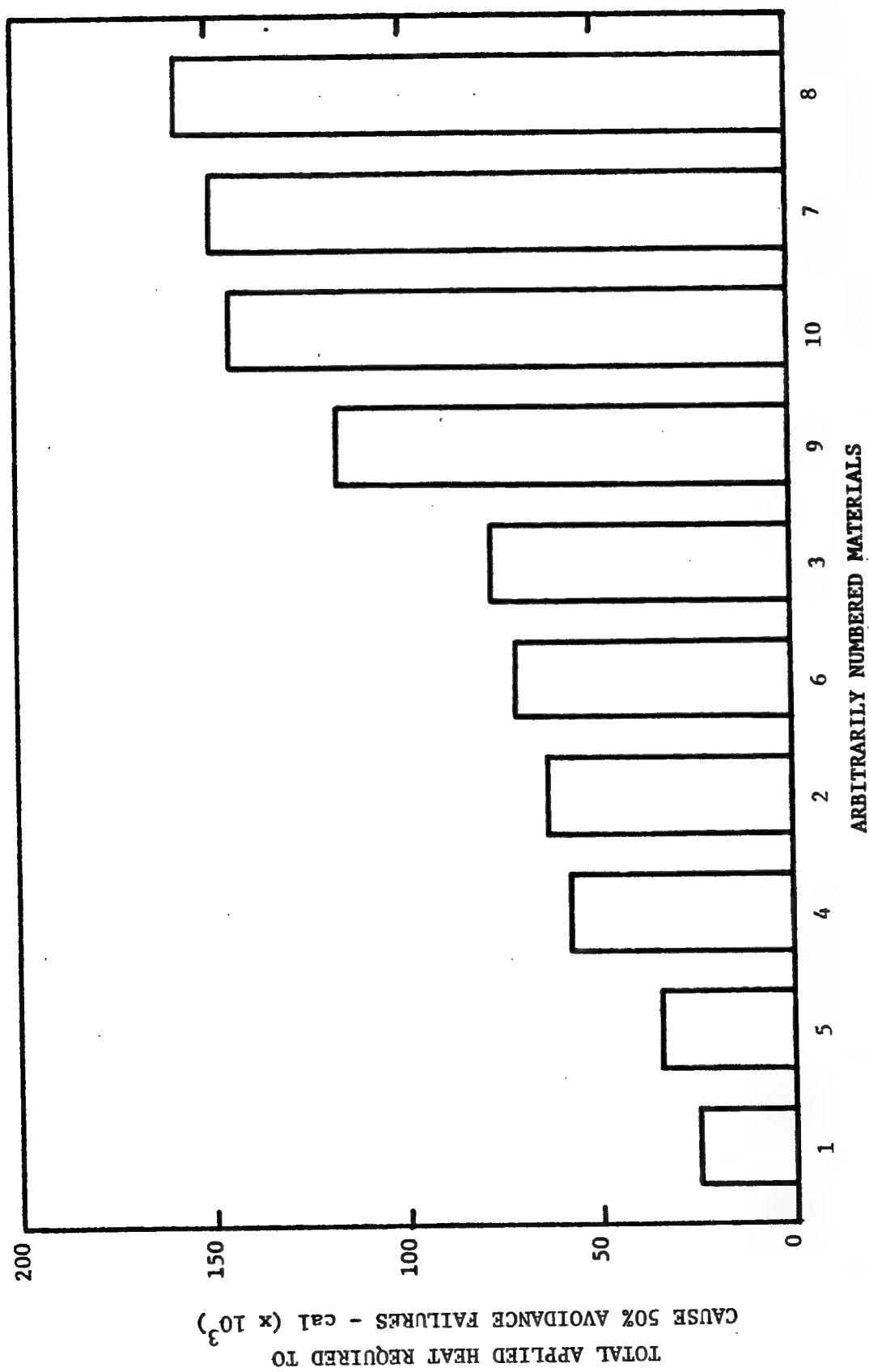


FIGURE 8 COMPARISON OF THE BEHAVIORALLY TOXIC HAZARD OF TEN FLEXIBLE, FIRE RETARDED POLYURETHANE FOAMS RANKED ACCORDING TO BEHAVIORAL INCAPACITATION

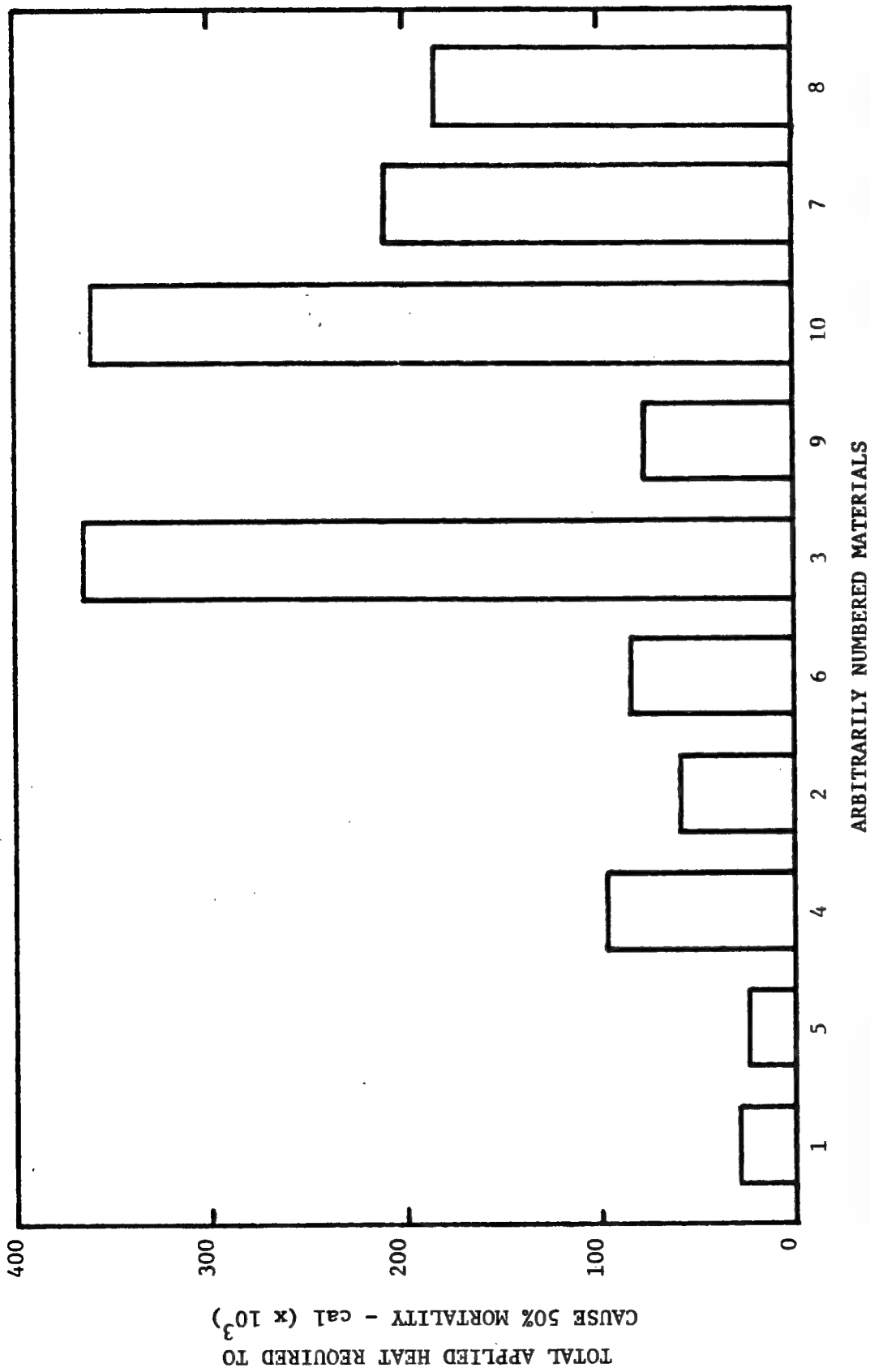


FIGURE 9 COMPARISON OF THE LETHAL HAZARD OF TEN FLEXIBLE, FIRE RETARDED POLYURETHANE FOAMS LISTED ACCORDING TO RELATIVE BEHAVIORAL INCAPACITATION

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